Synthesizing arbitrary photon states in a superconducting resonator

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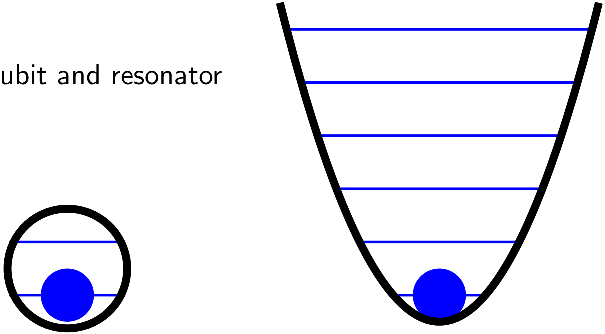
Collège de France, March 1 2010

Generation of quantum states in a resonator

Classical drive on qubit and resonator



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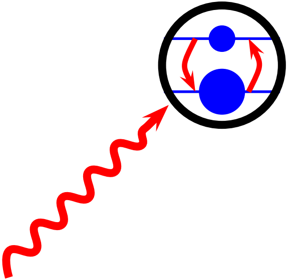

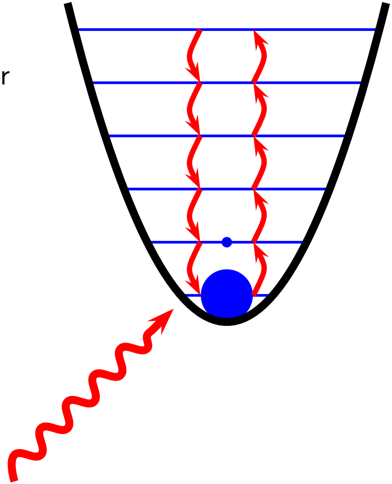

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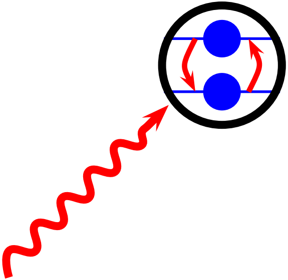

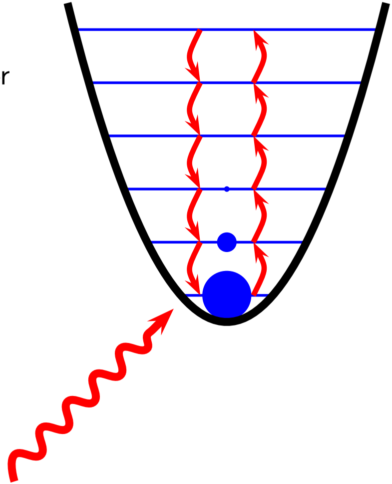

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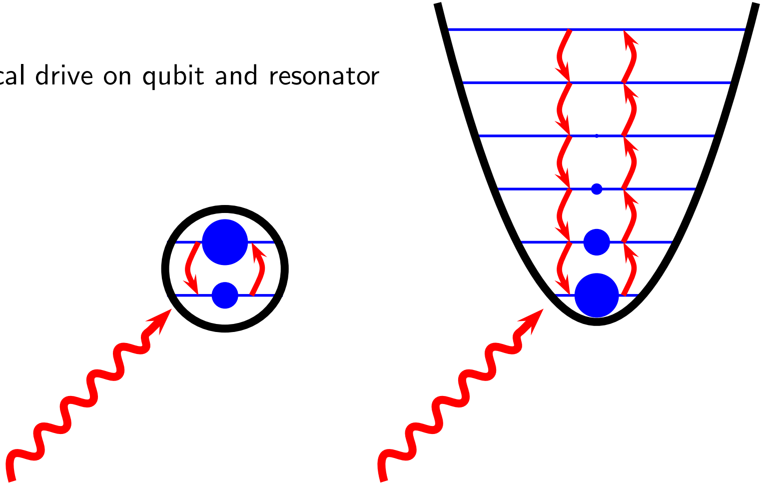

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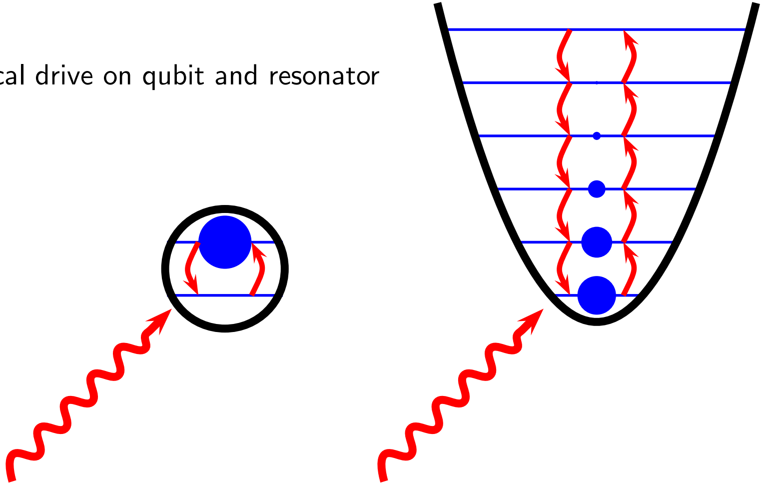

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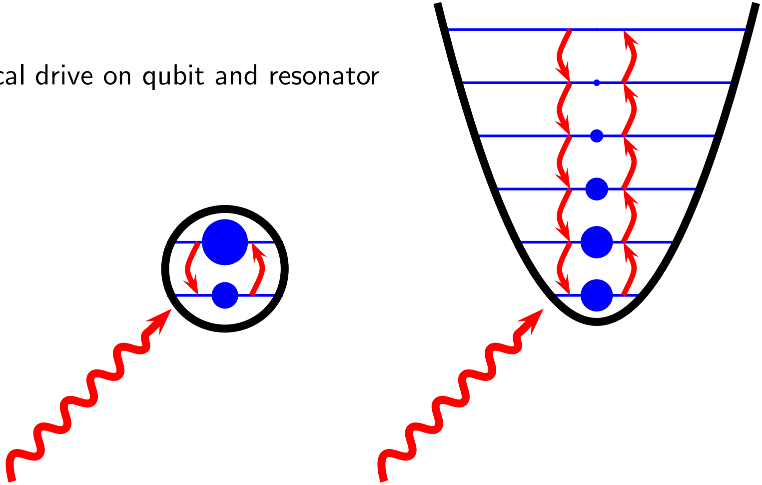

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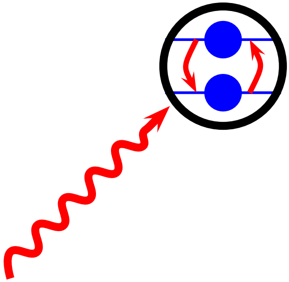

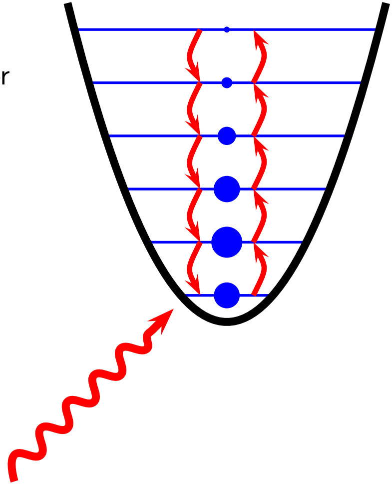

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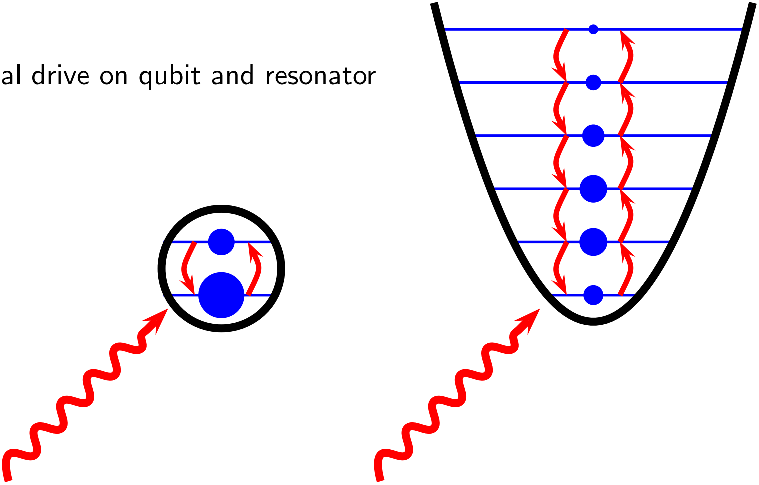

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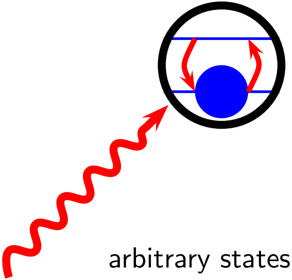
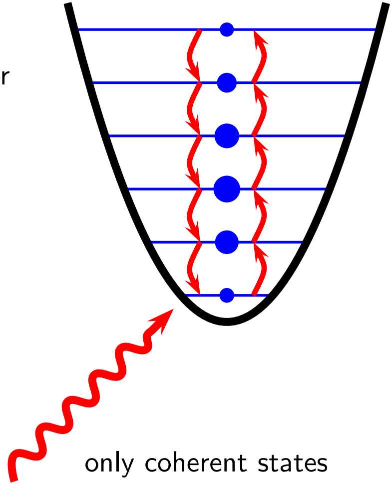


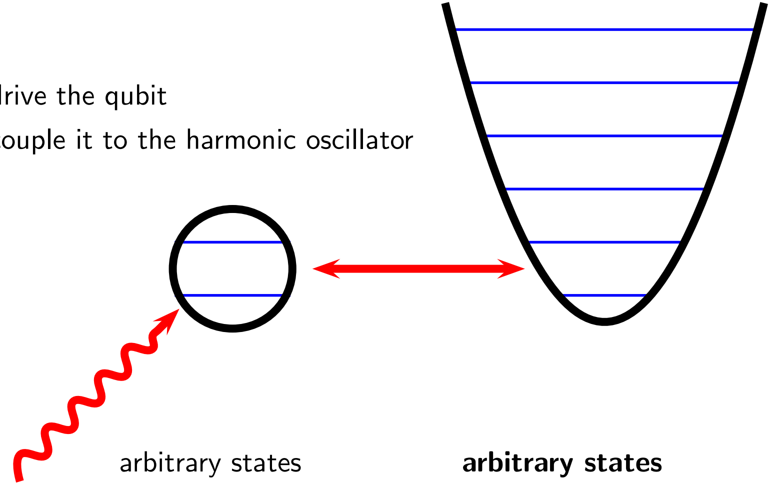
arbitrary states



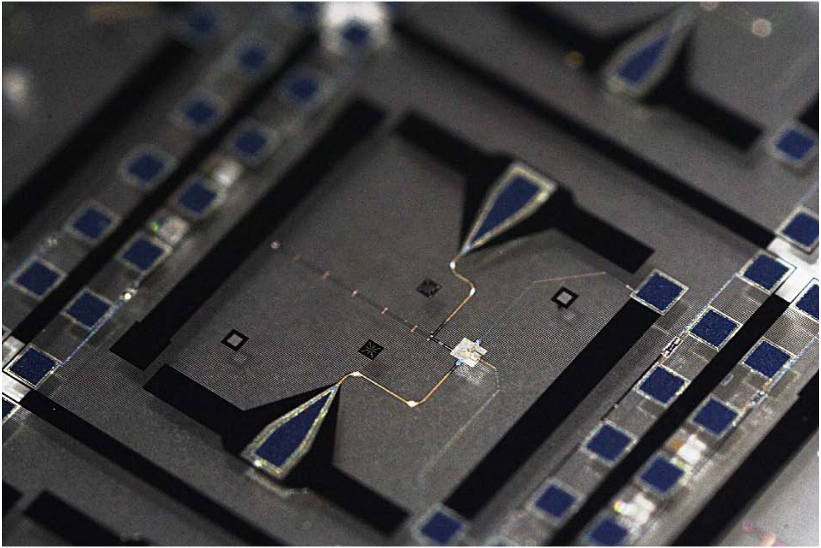
only coherent states

Generation of quantum states in a resonator

- drive the qubit
- couple it to the harmonic oscillator

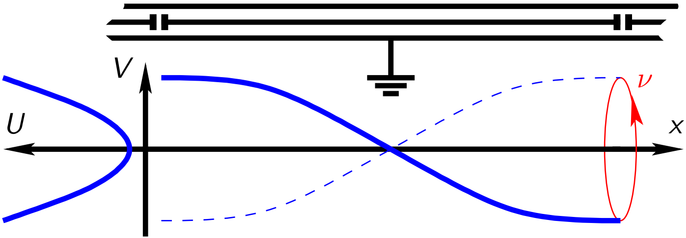


Device



die size: $6 \times 6\,\mathrm{mm}$

Coplanar waveguide resonator

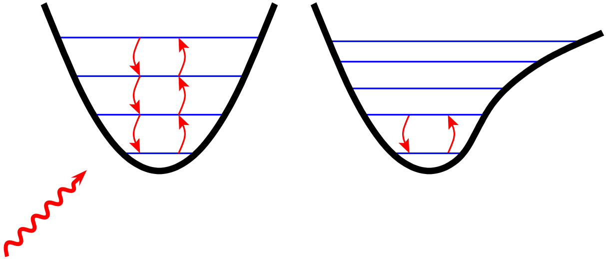


- very small capacitors are open ends
- each mode forms a quantum harmonic oscillator
- we use fundamental mode at frequency $\nu = \frac{c_{\text{eff}}}{2L}$
- make out of superconductor for high quality factor Q

Performance:

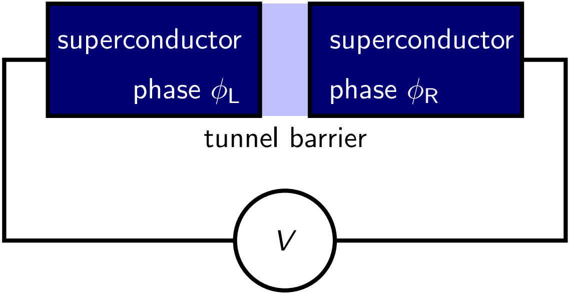
- $Q \sim 1 \ldots 5 \cdot 10^5$ or $T_1 \sim 2.5 \ldots 10\,\mu\text{s}$

Superconducting qubits



- 2 level system hard to make in a circuit
- very strong nonlinearity is enough
- allows to address 0—1 transition exclusively
- we use Josephson junction as nonlinear circuit element

Josephson junction



Dynamics are determined by:

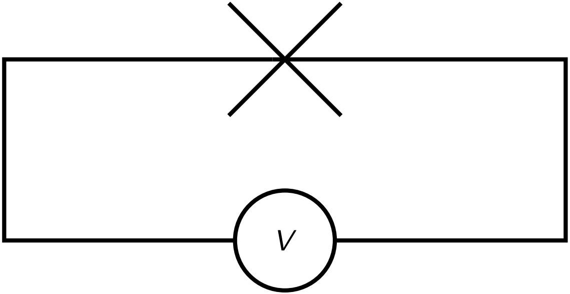
$$I = I_0 \sin\delta \quad \text{DC Josephson relation}$$

$$V = \frac{\hbar}{2e}\frac{\partial\delta}{\partial t} \quad \text{AC Josephson relation}$$

$\delta = \phi_L - \phi_R$ phase difference

I_0 critical current of junction

Josephson junction



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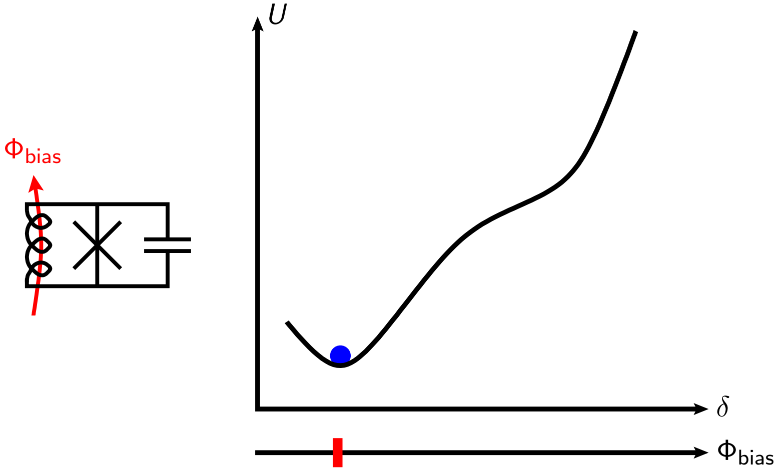
Superconducting phase qubit



$$H = \underbrace{\frac{\left(\frac{\hbar}{2e}\delta - \Phi_{\text{bias}}\right)^2}{2L} - \frac{\hbar}{2e} I_0 \cos\delta}_{U} + \frac{Q^2}{2C} \qquad [\delta, Q] = 2ei$$

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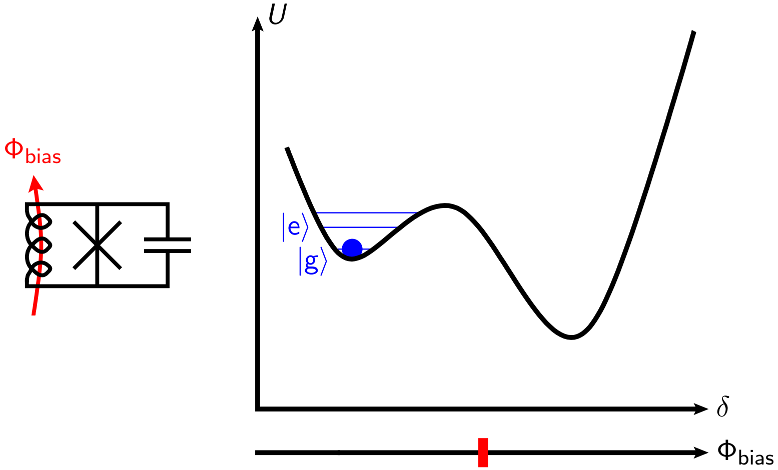

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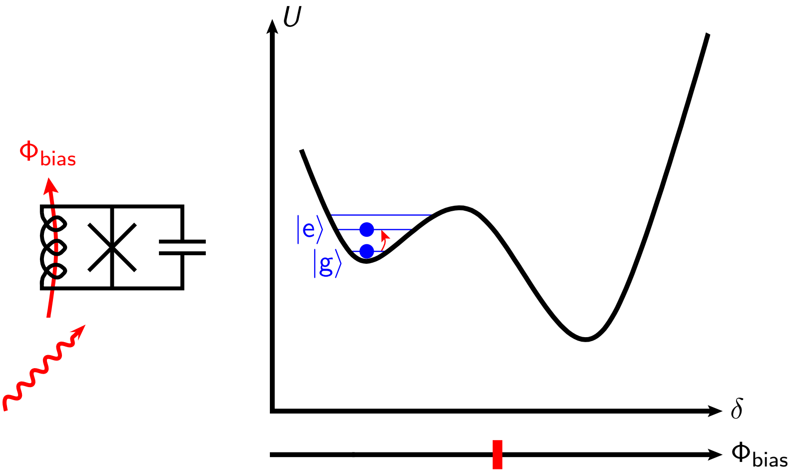

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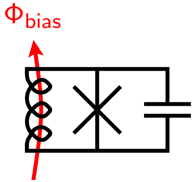

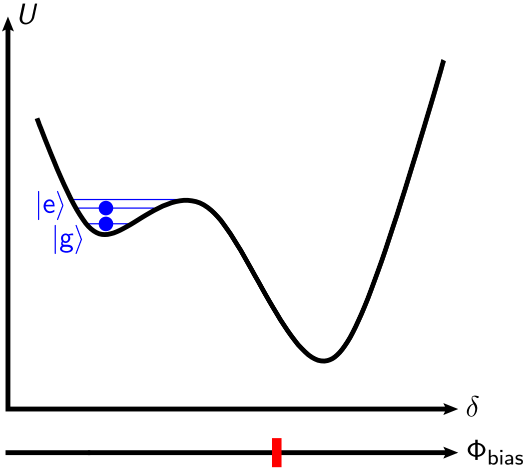

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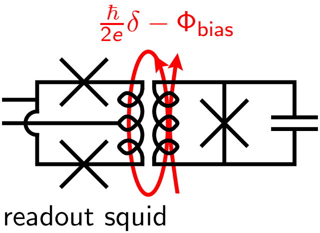

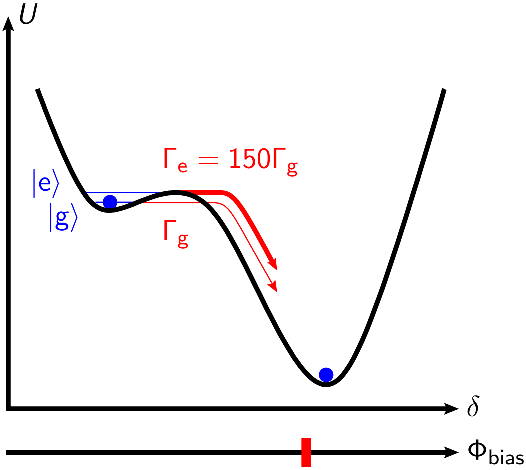

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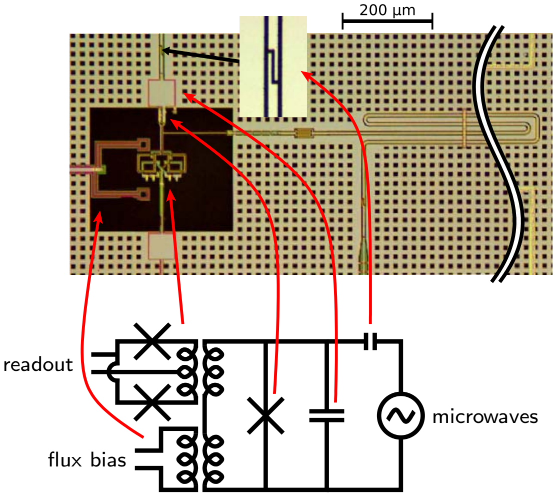
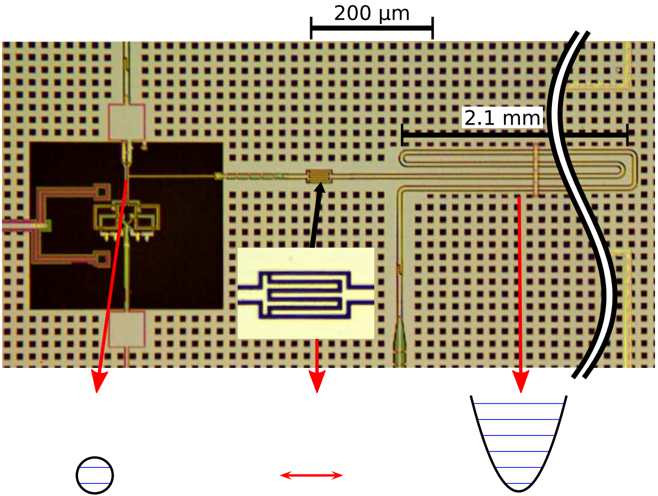
$$[\delta, Q] = 2ei$$

UCSB phase qubit



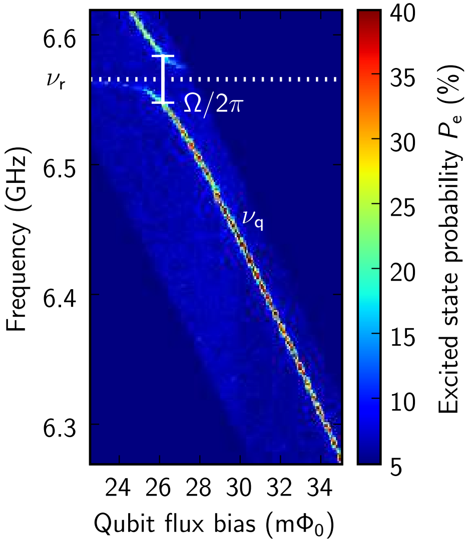
- energy relaxation time
  $T_1 \approx 600\,\mathrm{ns}$
- quality factor
  $Q \approx 2 \cdot 10^4$
- phase coherence time
  $T_2 \approx 150\,\mathrm{ns}$
- nonlinearity
  $\Delta \approx 200\,\mathrm{MHz}$
  limits gate time $\gtrapprox 10\,\mathrm{ns}$
- readout visibility
  $1 - P_{\text{`e'}|\text{g}} - P_{\text{`g'}|\text{e}} \approx 0.90$

Coupling qubit and resonator



$$H = h\nu_q \sigma^+\sigma^- \; + \; \frac{\hbar\Omega}{2}\left(a\sigma_+ + a^\dagger\sigma_-\right) \; + \; h\nu_r\left(a^\dagger a + \frac{1}{2}\right)$$

Spectroscopy of qubit-resonator coupling



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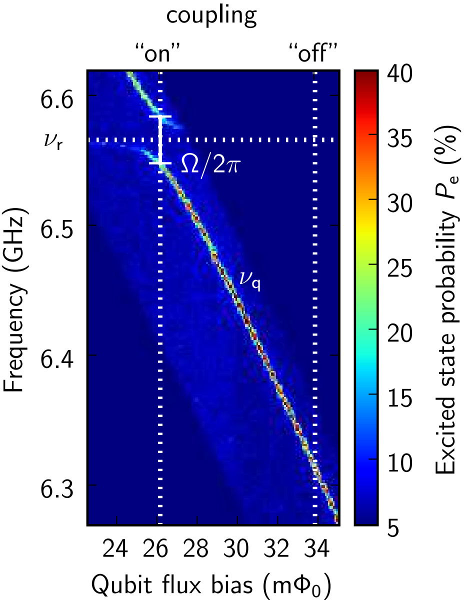
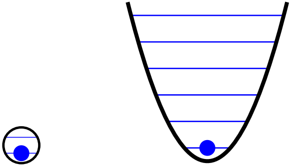
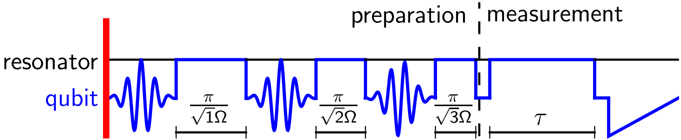


- high probability indicates eigenfrequencies of qubit-resonator system
- Qubit and resonator only interact when $\nu_q \approx \nu_r$
- Coupling can be turned on and off

Generating Fock states: Pumping photons one by one



$$H_{\text{int}} = \frac{\hbar\Omega}{2}\left(a\sigma_+ + a^\dagger\sigma_-\right)$$
$$\propto \sqrt{\text{total photon number}}$$



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π-pulse: $> 98\,\%$ fidelity

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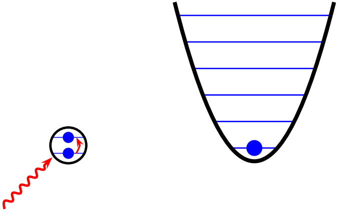

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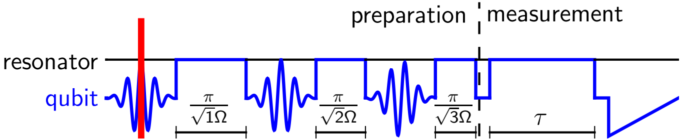

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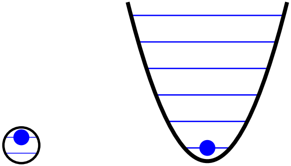

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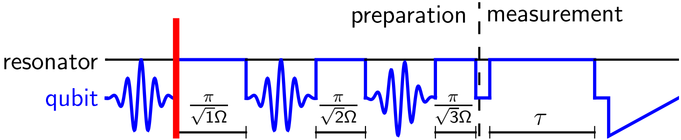

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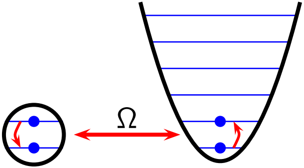

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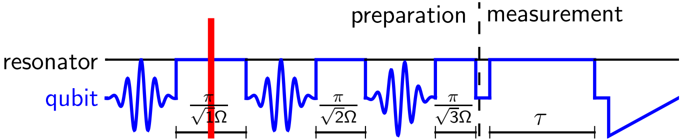

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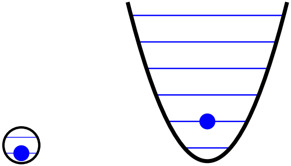

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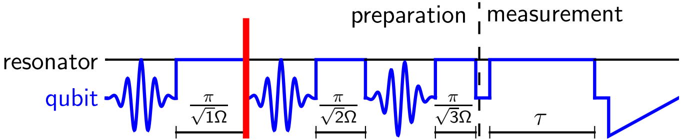

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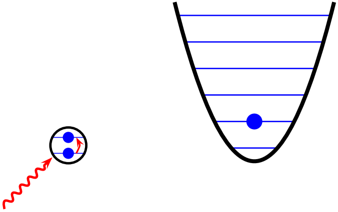

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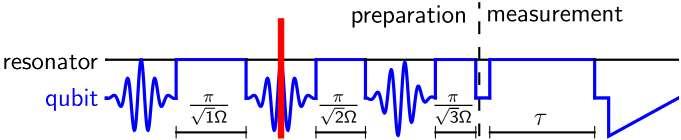

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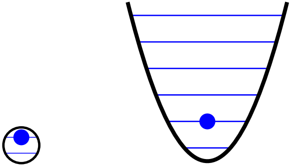

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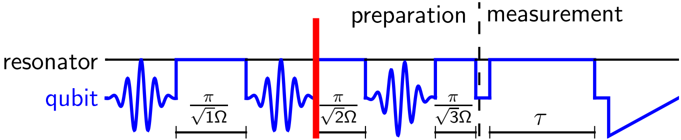

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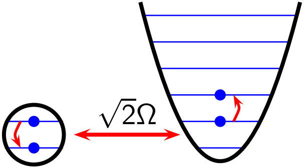

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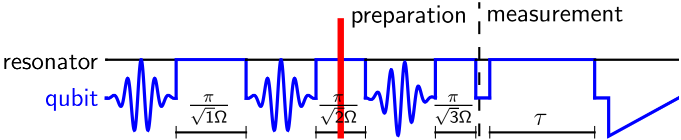

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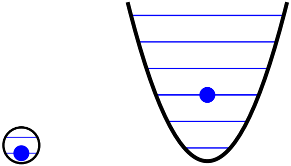

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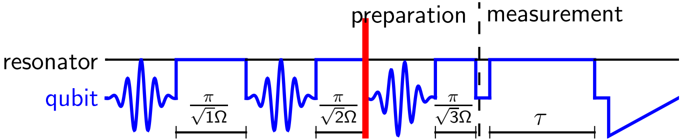

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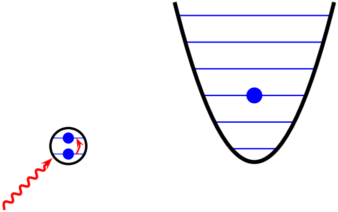

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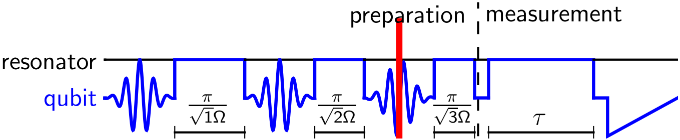

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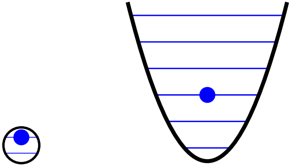

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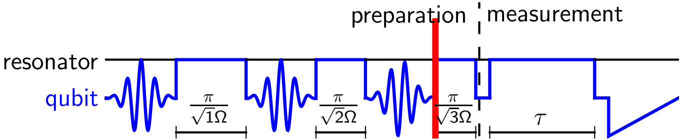

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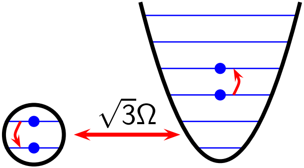
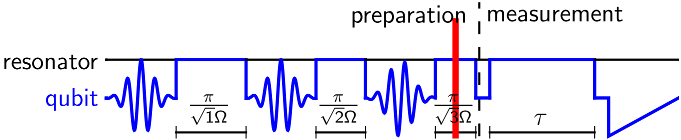


$$H_{\text{int}} = \frac{\hbar\Omega}{2}\left(a\sigma_+ + a^\dagger\sigma_-\right)$$
$$\propto \sqrt{\text{total photon number}}$$



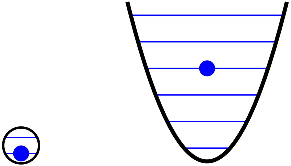
Only possible with good pulses:

π-pulse: $> 98\,\%$ fidelity

swap-pulse: $> 98\,\%$ fidelity

E. Lucero *et al.* PRL **100**, 247001 (2008)

Generating Fock states: Pumping photons one by one



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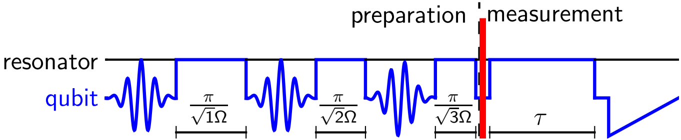

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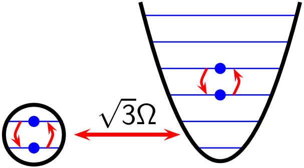
Generating Fock states: Pumping photons one by one



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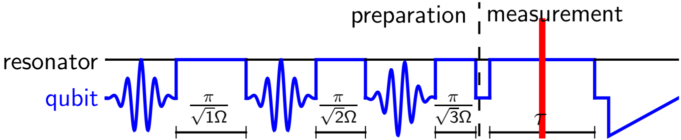

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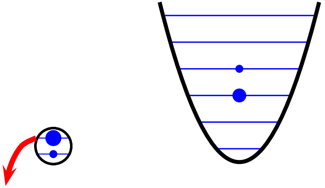

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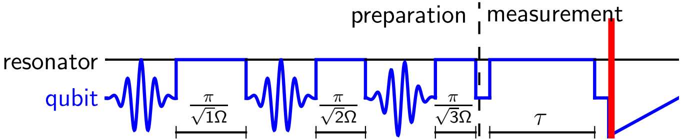

Only possible with good pulses:
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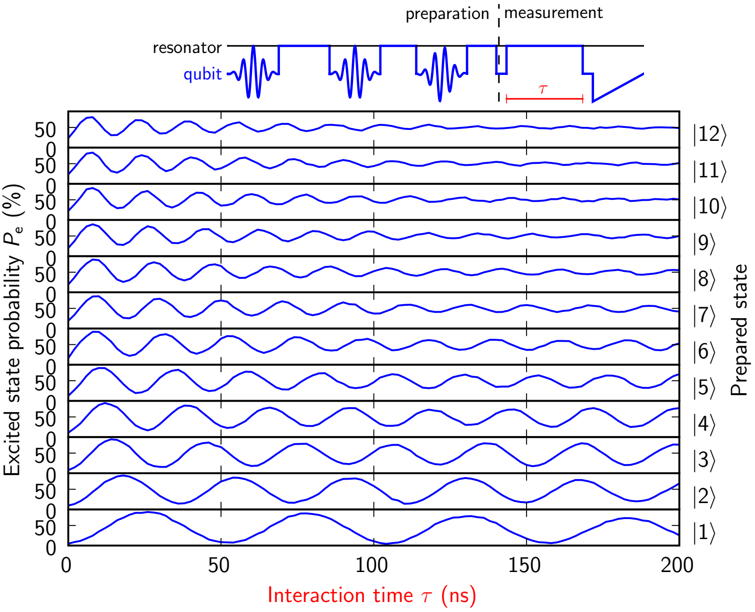
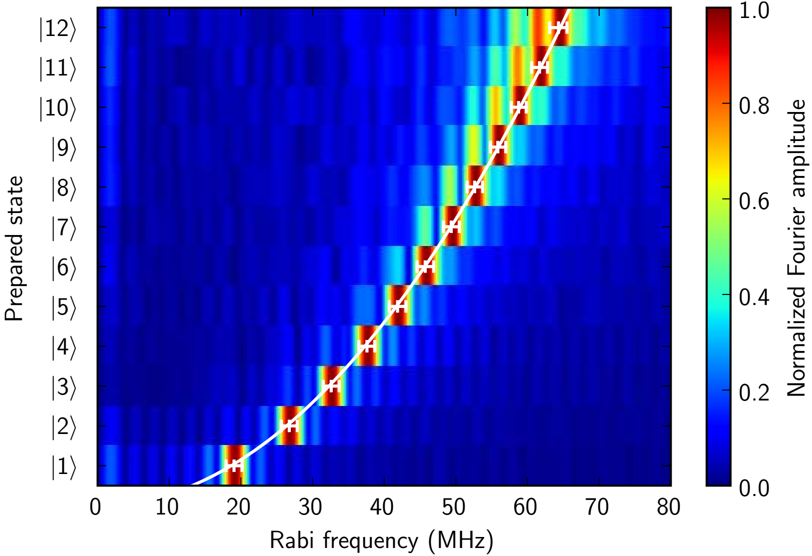
swap-pulse: $> 98\,\%$ fidelity

E. Lucero *et al.* PRL **100**, 247001 (2008)

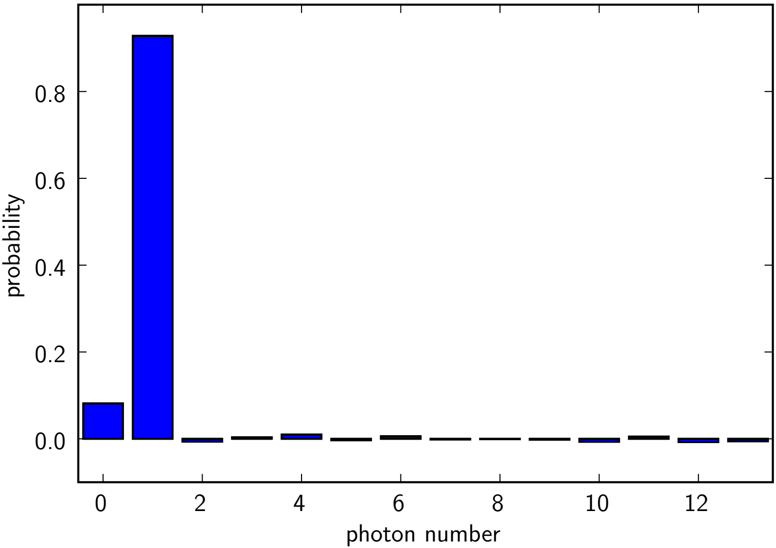
Fock states: Clear Rabi oscillations



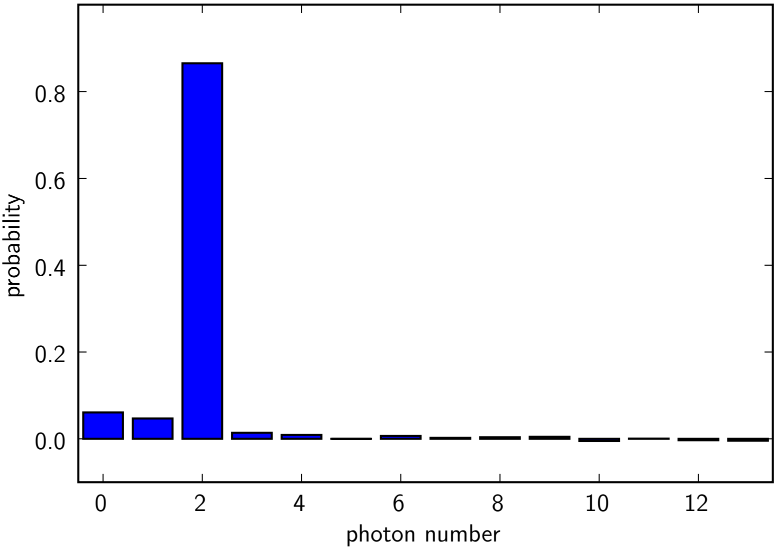
Fock states: Rabi frequencies scale as $\sqrt{n}$



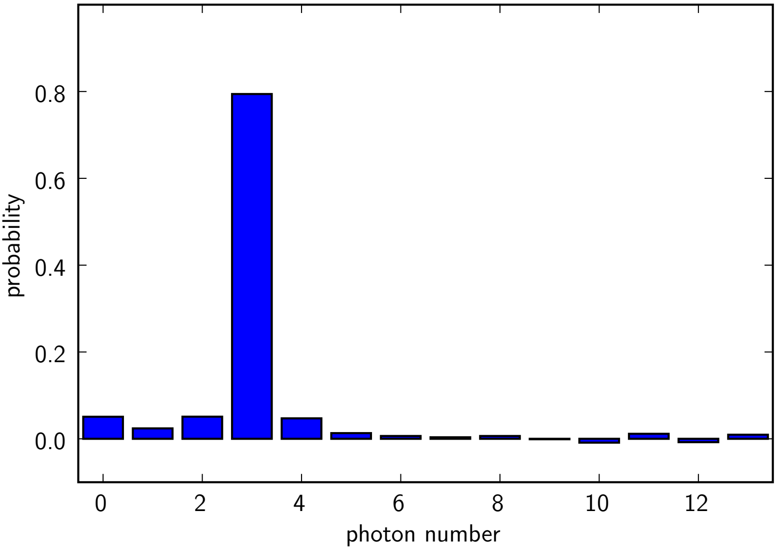
Fock states: Photon number distribution for $|1\rangle$



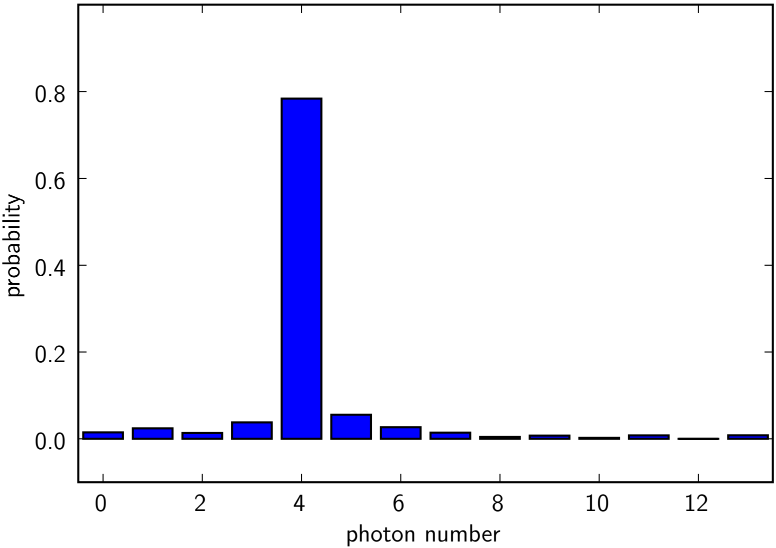
Fock states: Photon number distribution for $|2\rangle$



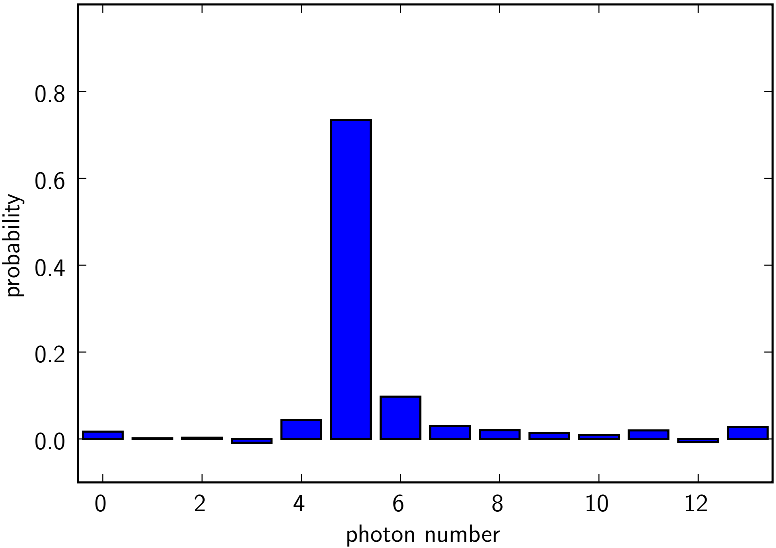
Fock states: Photon number distribution for $|3\rangle$



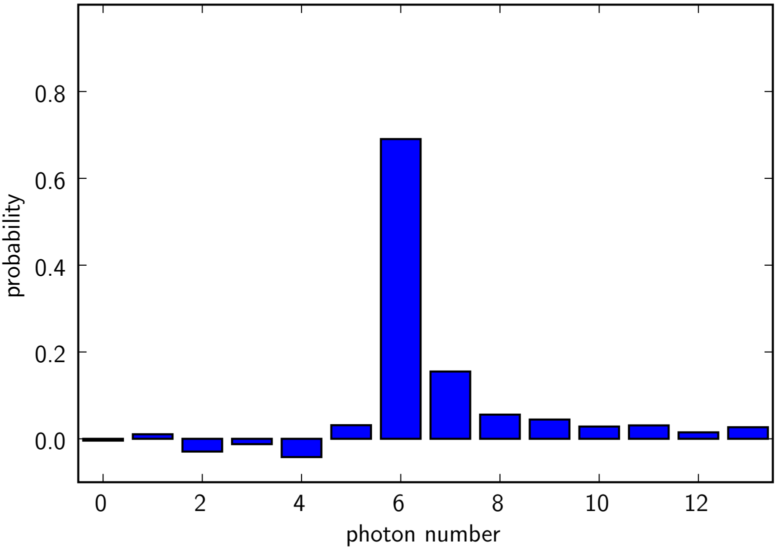
Fock states: Photon number distribution for $|4\rangle$



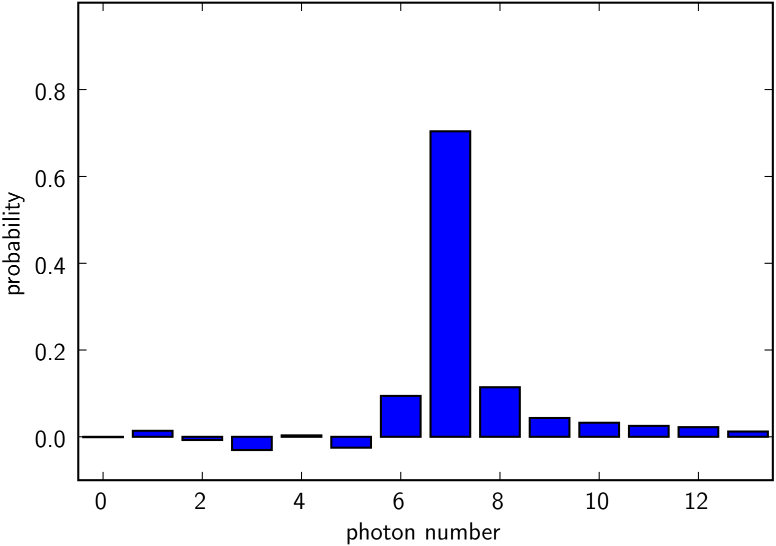
Fock states: Photon number distribution for $|5\rangle$



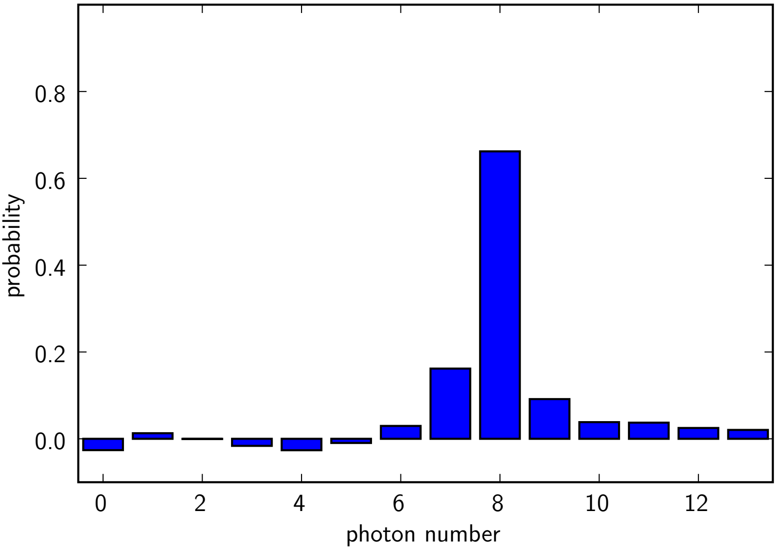
Fock states: Photon number distribution for $|6\rangle$



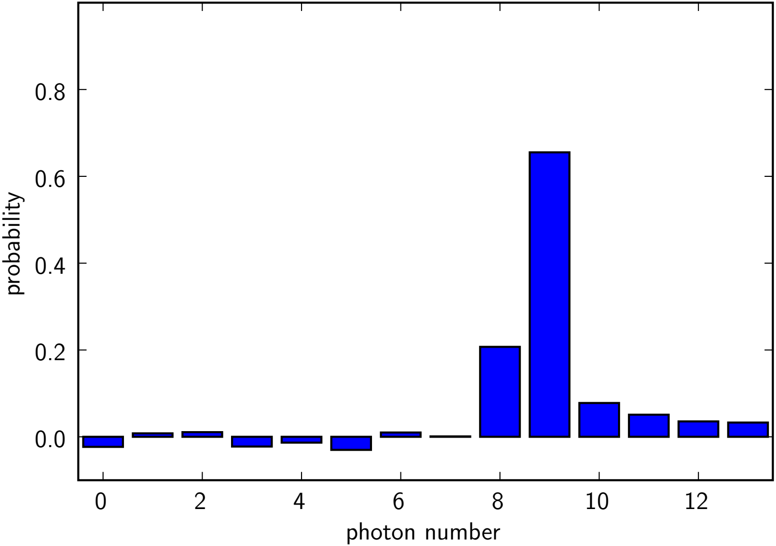
Fock states: Photon number distribution for $|7\rangle$



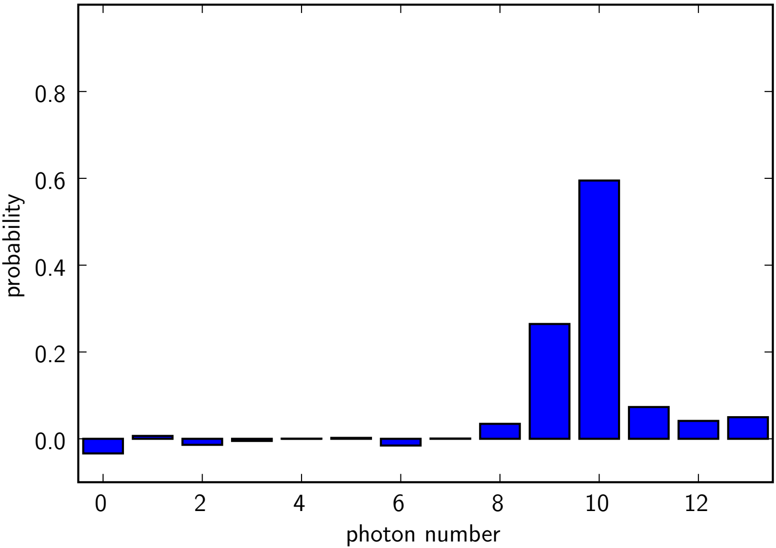
Fock states: Photon number distribution for $|8\rangle$



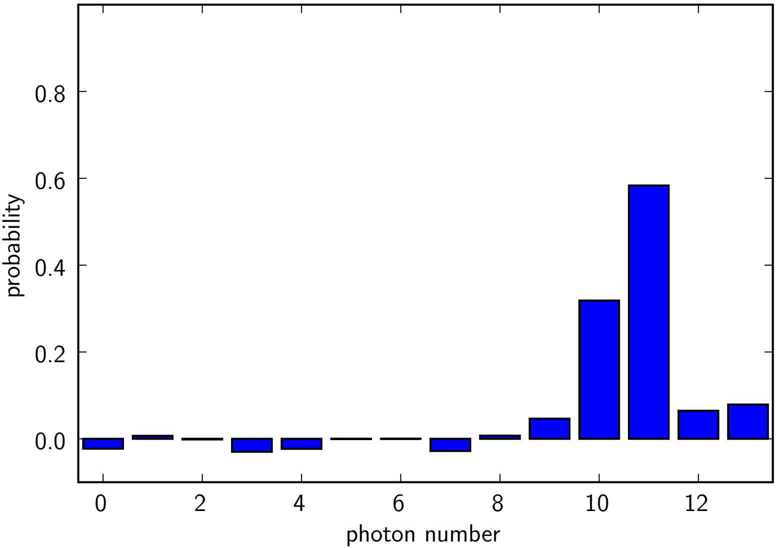
Fock states: Photon number distribution for $|9\rangle$



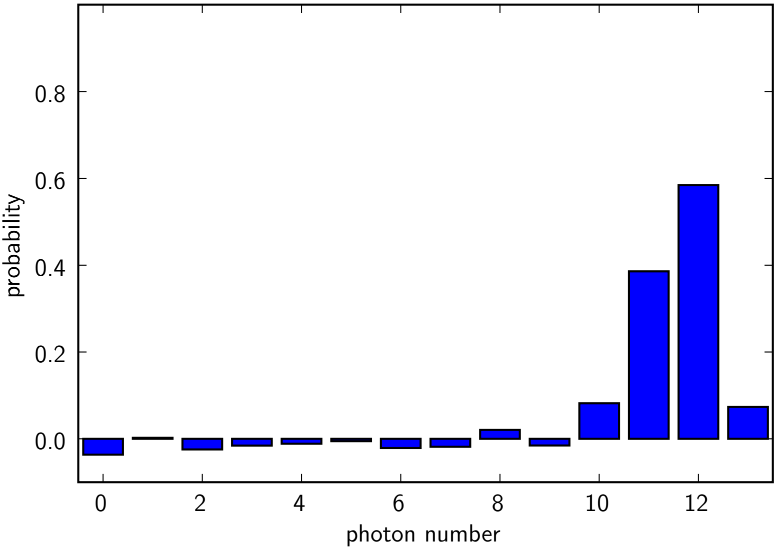
Fock states: Photon number distribution for $|10\rangle$



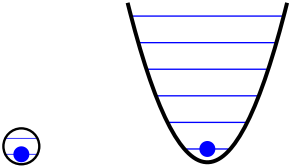
Fock states: Photon number distribution for $|11\rangle$



Fock states: Photon number distribution for $|12\rangle$

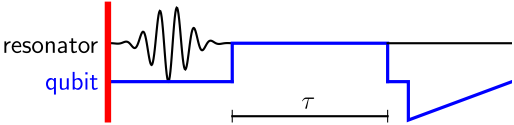


Directly driving the resonator creates a coherent state



Probabilities for Fock states are Poisson distributed

$$P_n(a = |\alpha^2|) = \frac{a^n e^{-a}}{n!}$$



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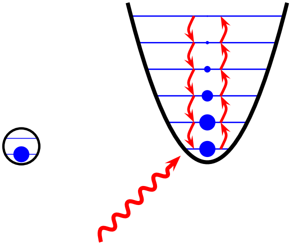

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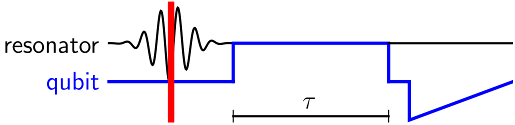

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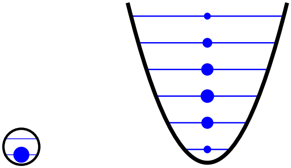

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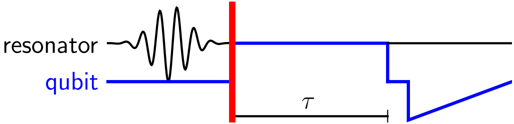

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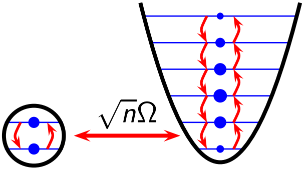

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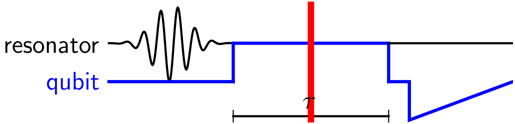

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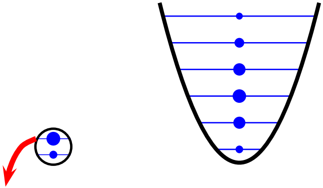

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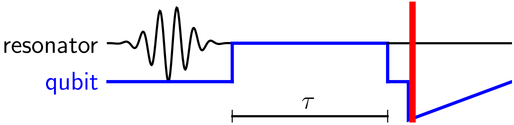
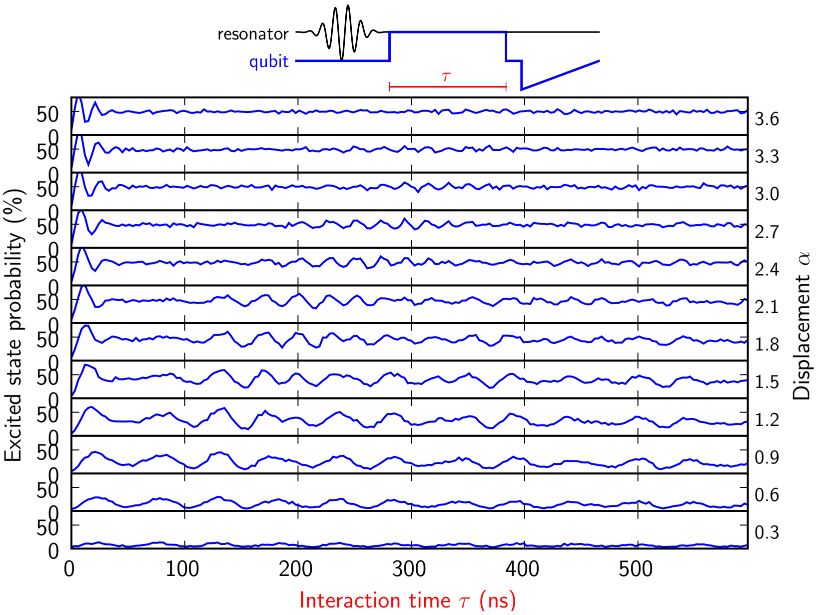
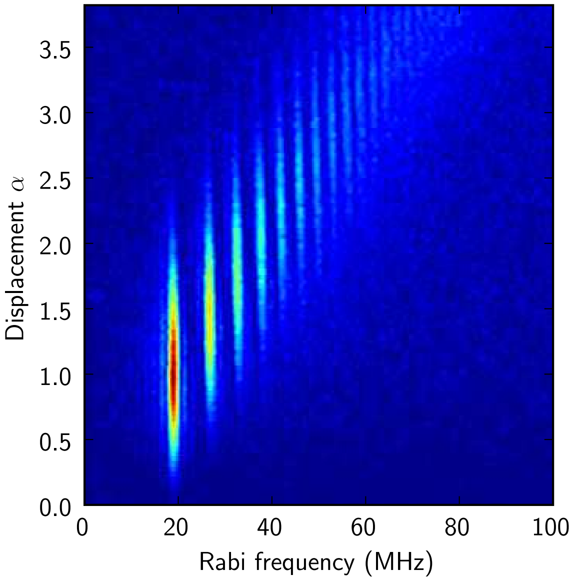


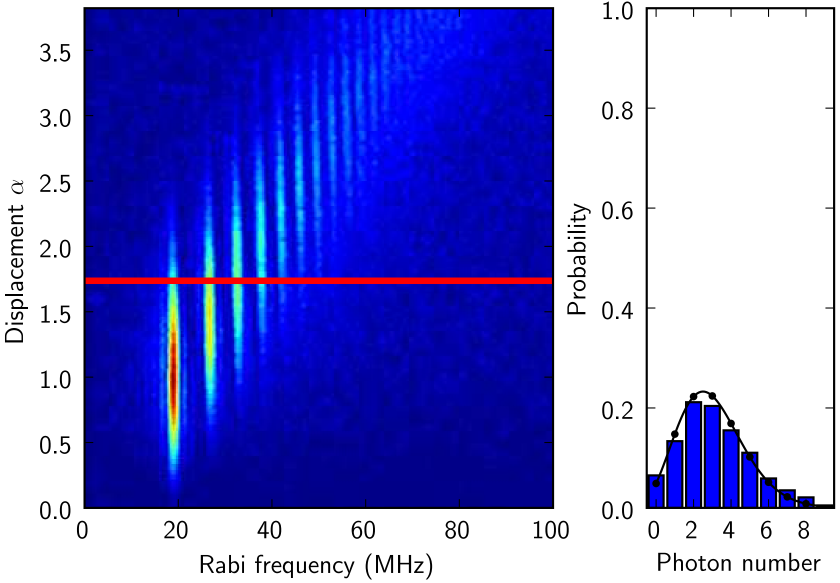
Coherent state: Non-periodic time traces



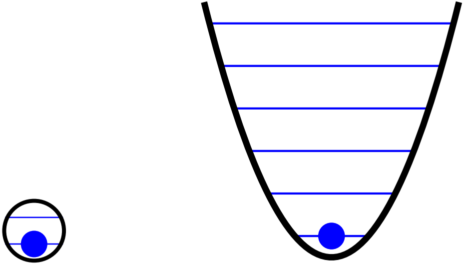
Coherent state: Superposition of Fock states



Coherent state: Superposition of Fock states

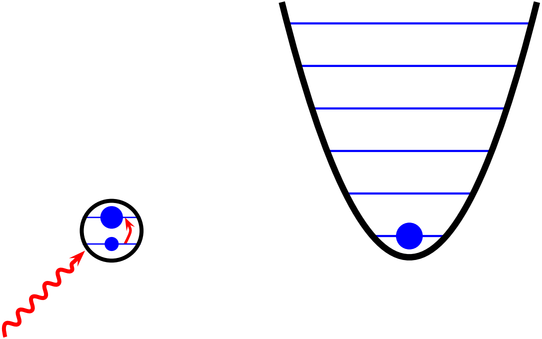


Generalizing the pump sequence to arbitrary states



- only perform partial state transfers
- leave some probability behind

Generalizing the pump sequence to arbitrary states



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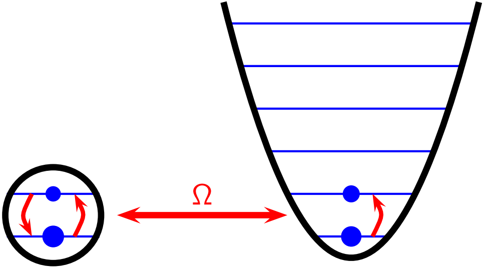

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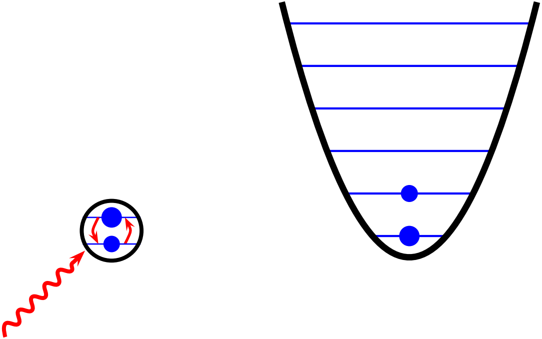

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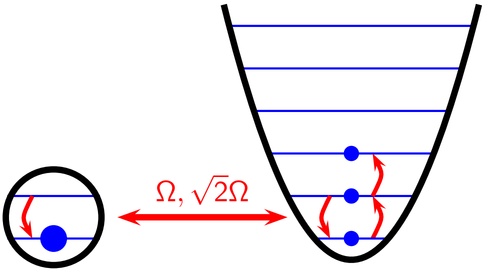

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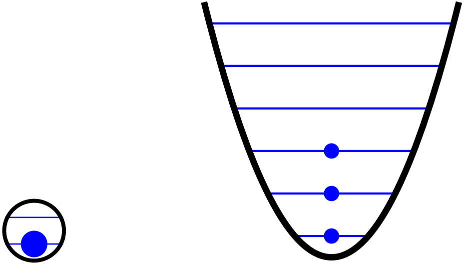
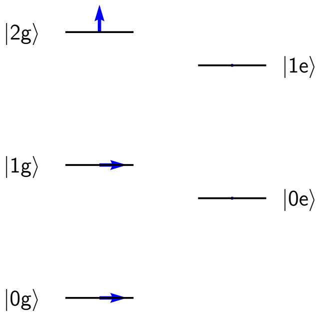


- qubit and resonator entangled during sequence
- phases matter
- swaps act on several photon numbers

Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = \frac{1}{\sqrt{3}}(|0\rangle + |1\rangle + i|2\rangle)|g\rangle$$



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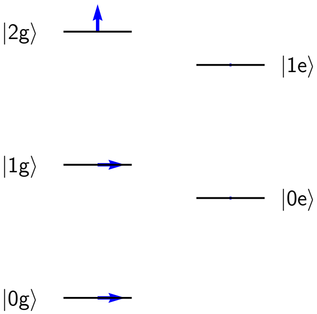


Time-reversed problem easier:

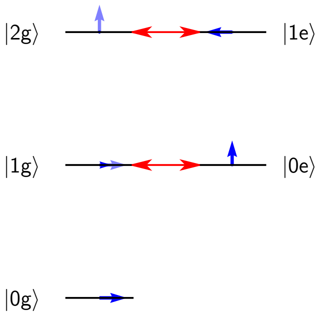
- start with the desired state
- eliminate states from top to bottom

Law, Eberly, PRL **76**, 1055 (1996)

resonator

qubit

Algorithm for arbitrary states: "Reverse Engineering"

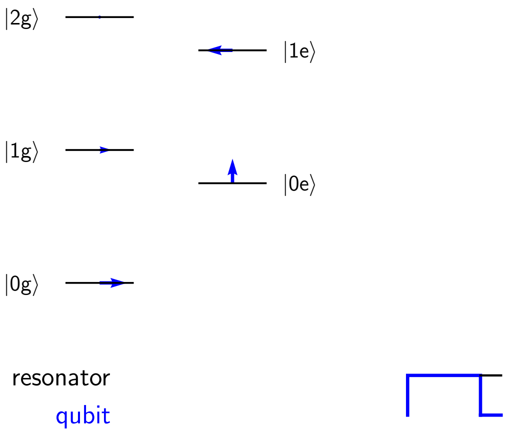


resonator

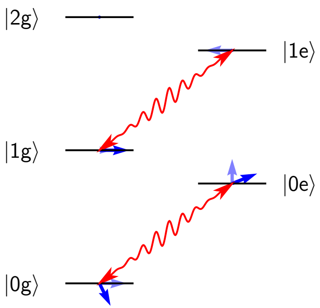
qubit

Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = (0.577|0\rangle + 0.256|1\rangle)|g\rangle + (0.517i|0\rangle - 0.577|1\rangle)|e\rangle$$



Algorithm for arbitrary states: “Reverse Engineering”

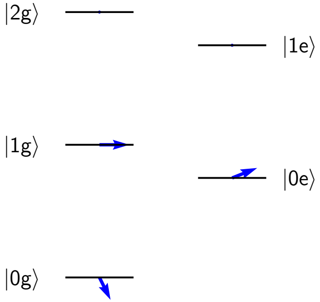


2 × 2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase

Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = ((0.234 - 0.473i)|0\rangle + 0.632|1\rangle)|g\rangle + (0.528 + 0.210i)|0\rangle|e\rangle$$



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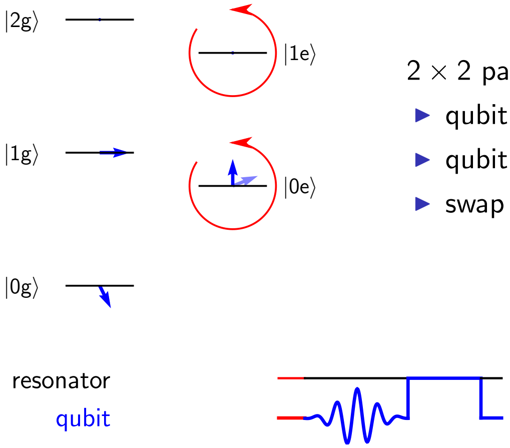
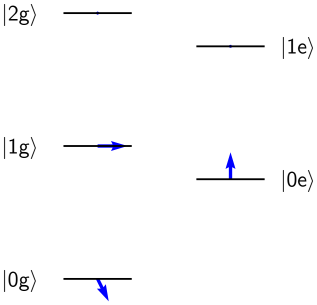


2 × 2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase
- swap phase

Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = ((0.234 - 0.473i)|0\rangle + 0.632|1\rangle)|g\rangle + (0.568i|0\rangle)|e\rangle$$



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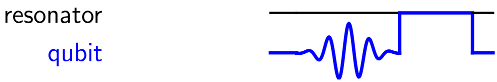
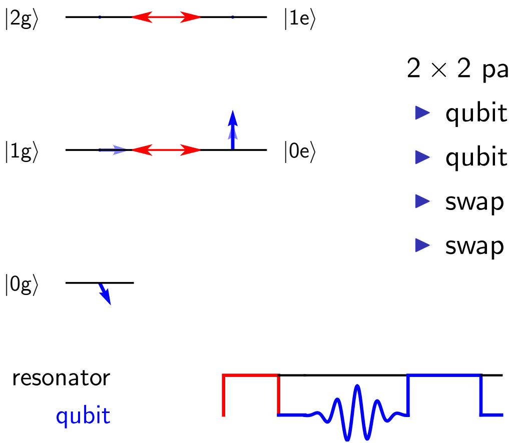


Algorithm for arbitrary states: "Reverse Engineering"

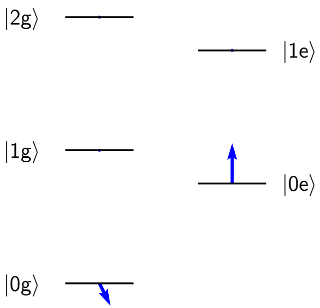


2 × 2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase
- swap phase
- swap amplitude

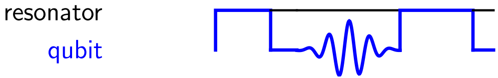
Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = ((0.234 - 0.473i)|0\rangle)|g\rangle + (0.849i|0\rangle)|e\rangle$$

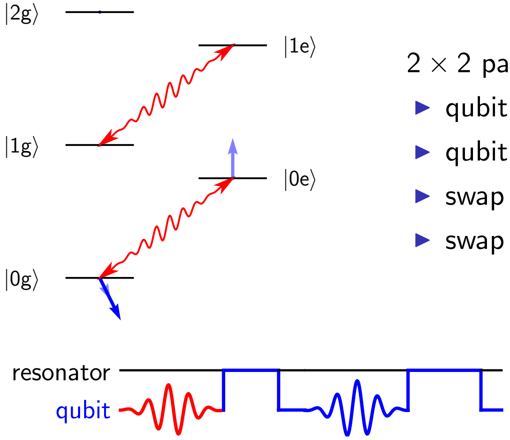


2 × 2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase
- swap phase
- swap amplitude



Algorithm for arbitrary states: "Reverse Engineering"

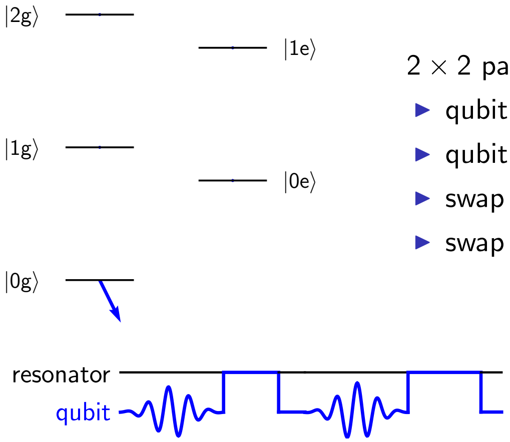


2 × 2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase
- swap phase
- swap amplitude

Algorithm for arbitrary states: "Reverse Engineering"

$$|\psi\rangle = (0.444 - 0.896i)|0\rangle|g\rangle$$



2×2 parameters per photon step:

- qubit drive pulse amplitude
- qubit drive pulse phase
- swap phase
- swap amplitude

Calibrations

- impulse response (sampling scope)
- imperfections of IQ-mixer (spectrum analyzer)
- cable response (qubit as sampling scope)

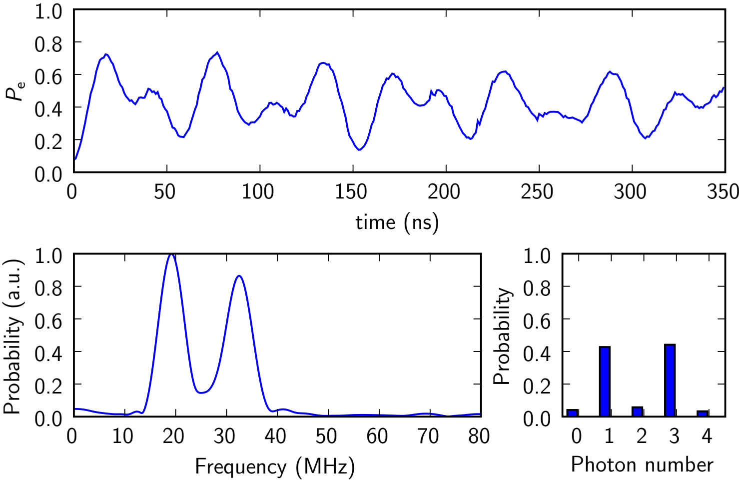
- various parameters for readout SQUID
- π pulses (amplitude and frequency)
- measure pulse amplitude
- swap pulse amplitude
- swap pulse time for each photon number
- first order correction for finite rise time of swap pulses
- qubit/resonator dephasing rate when off resonance
- resonator displacement/drive amplitude ratio
- resonator drive phase
- readout visibility

BUT:

- **no per-state calibrations; just run the calculated sequence**

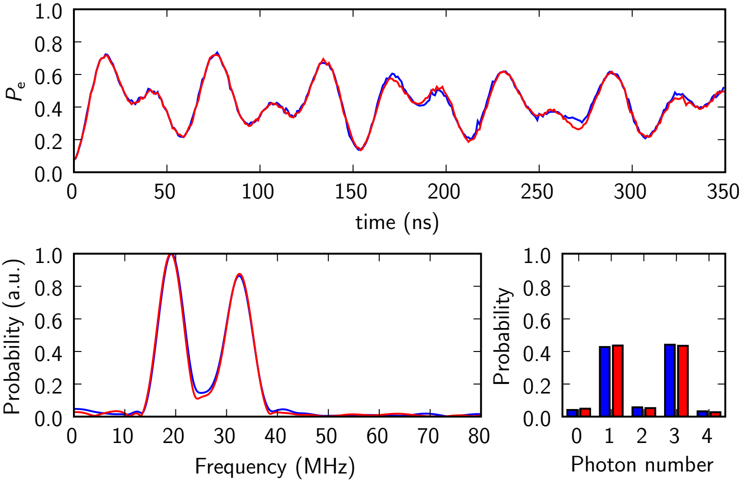
A superposition of $|1\rangle$ and $|3\rangle$

$|\psi\rangle = |1\rangle + |3\rangle$



A superposition of $|1\rangle$ and $|3\rangle$

$|\psi\rangle = |1\rangle + |3\rangle$ and $|\phi\rangle = |1\rangle + i|3\rangle$ look the same!

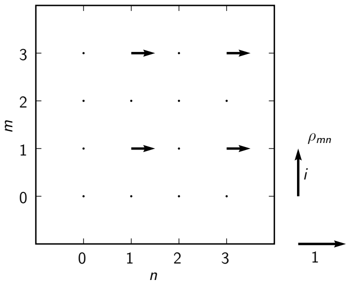


Full description of a resonator state

Example: $|\psi\rangle = |1\rangle + \;|3\rangle$

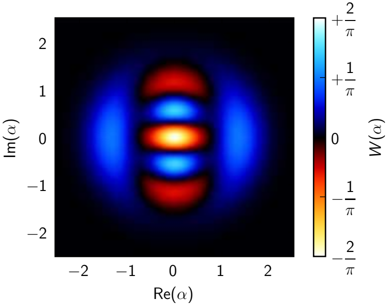
Density matrix:

$$\rho = |\psi\rangle\langle\psi|$$



Wigner function:

$$W(\alpha) = \frac{2}{\pi}\langle\psi|D^\dagger(-\alpha)\Pi D(-\alpha)|\psi\rangle$$

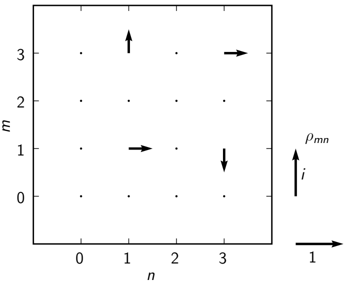


Full description of a resonator state

Example: $|\psi\rangle = |1\rangle + i|3\rangle$

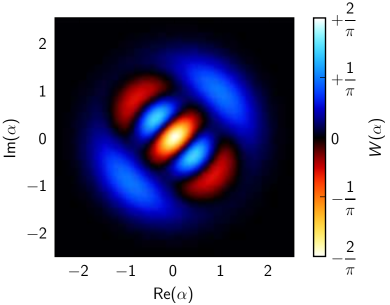
Density matrix:

$$\rho = |\psi\rangle\langle\psi|$$

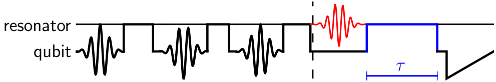


Wigner function:

$$W(\alpha) = \frac{2}{\pi}\langle\psi|D^\dagger(-\alpha)\Pi D(-\alpha)|\psi\rangle$$



Wigner tomography: measurement protocol

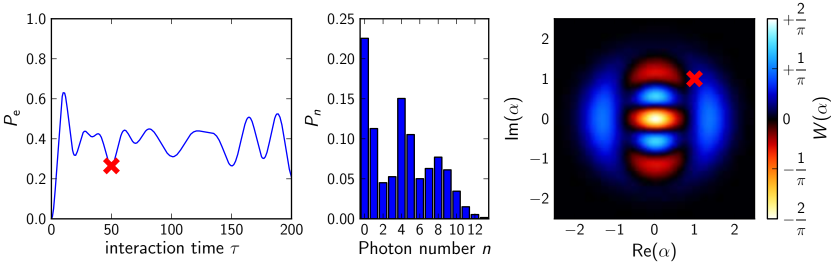


Preparation of state $|\psi\rangle$
(Law & Eberly protocol)

$$\rho = F^2 |\psi\rangle\langle\psi| + \dots$$

State reconstruction

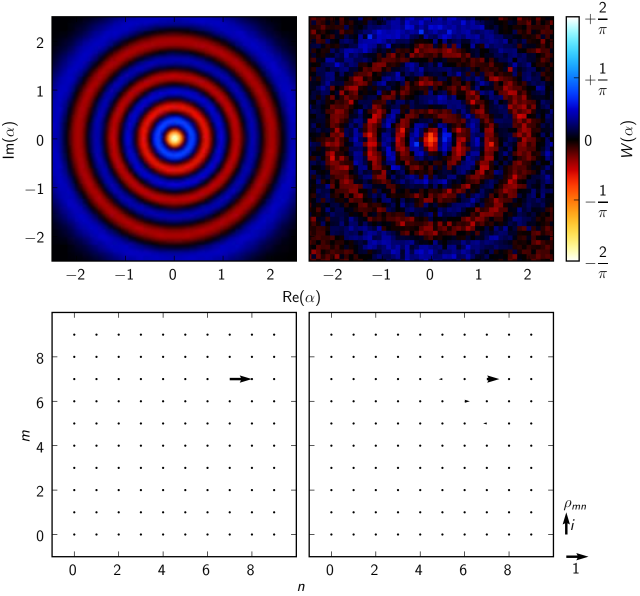
- displacement: $\rho \to \rho_\alpha = D(-\alpha)\rho D(\alpha)$
- qubit–resonator interaction for time τ
- qubit measurement



$$W(\alpha) = \frac{2}{\pi}\mathrm{Tr}\left(\rho_\alpha \Pi\right) = \frac{2}{\pi}\sum_{n=0}^{\infty}(-1)^n P_n$$

Controlling photon number

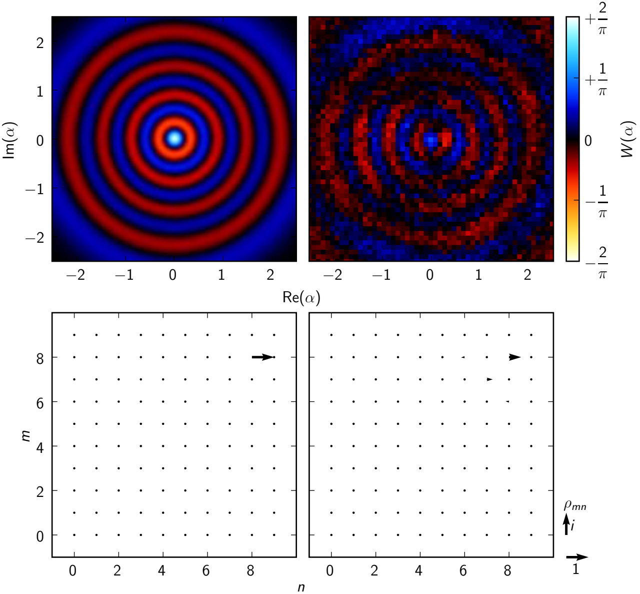
$|\psi\rangle = |7\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.75$

Controlling photon number

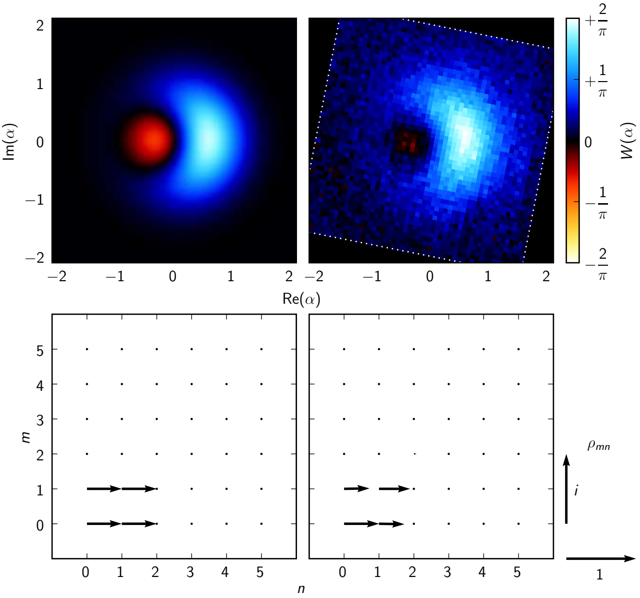
$|\psi\rangle = |8\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.72$

Controlling superpositions

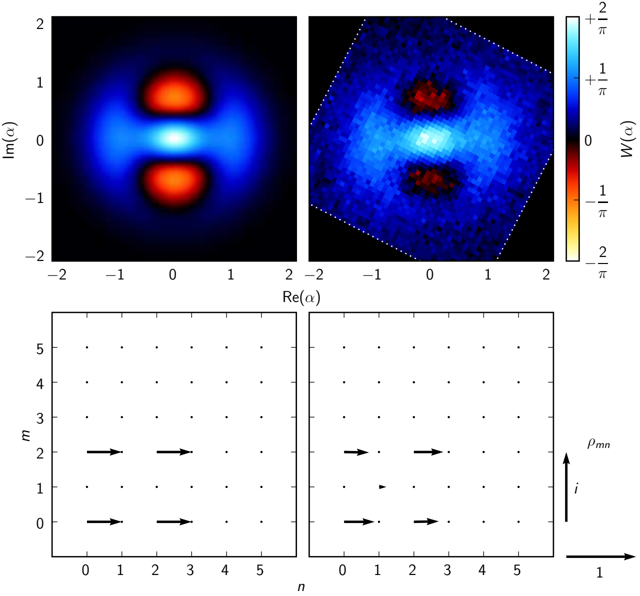
$|\psi\rangle = |0\rangle + |1\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.92$

Controlling superpositions

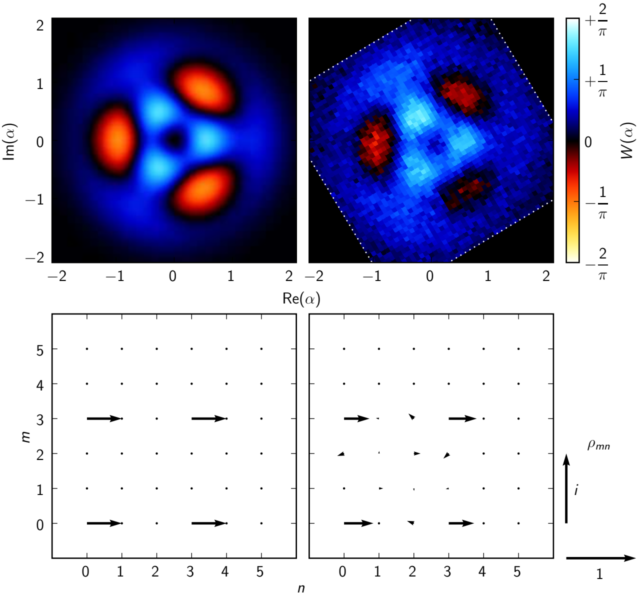
$|\psi\rangle = |0\rangle + |2\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.89$

Controlling superpositions

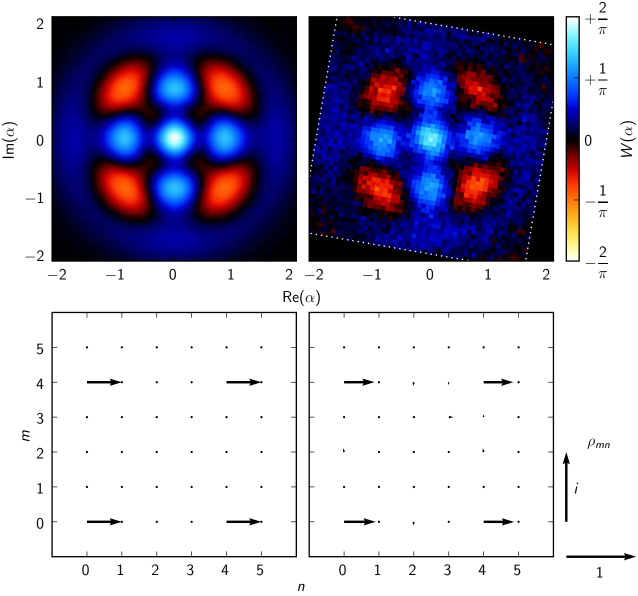
$|\psi\rangle = |0\rangle + |3\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.88$

Controlling superpositions

$|\psi\rangle = |0\rangle + |4\rangle$

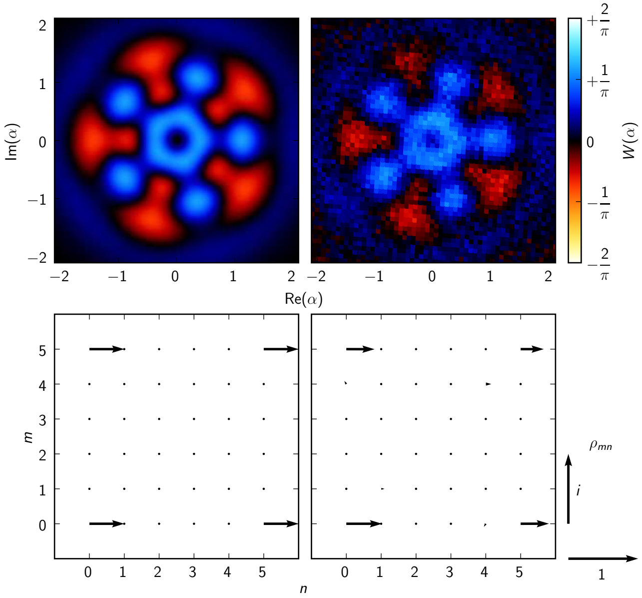


Fidelity:

$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.94$

Controlling superpositions

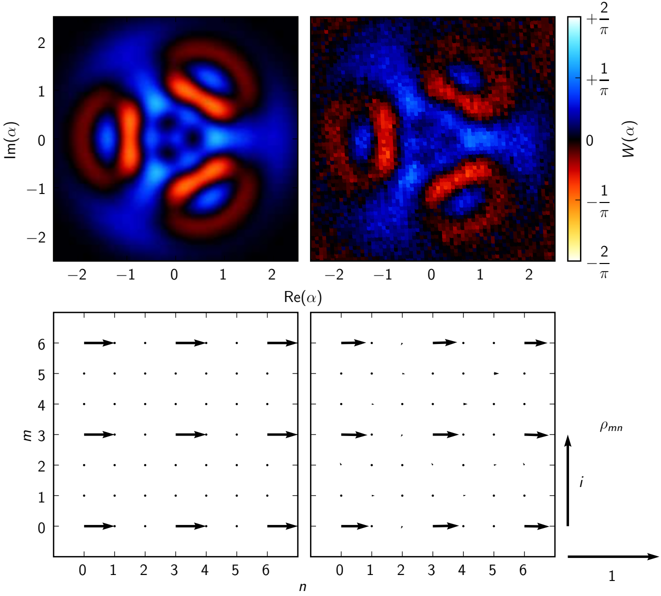
$|\psi\rangle = |0\rangle + |5\rangle$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.91$

Controlling phase

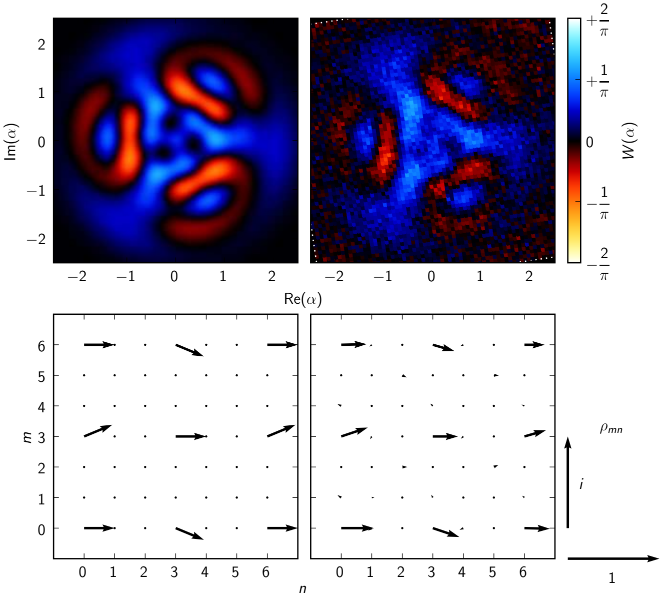
$$|\psi\rangle = |0\rangle + e^{\frac{0}{8}i\pi}|3\rangle + |6\rangle$$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.91$

Controlling phase

$$|\psi\rangle = |0\rangle + e^{\frac{1}{8}i\pi}|3\rangle + |6\rangle$$

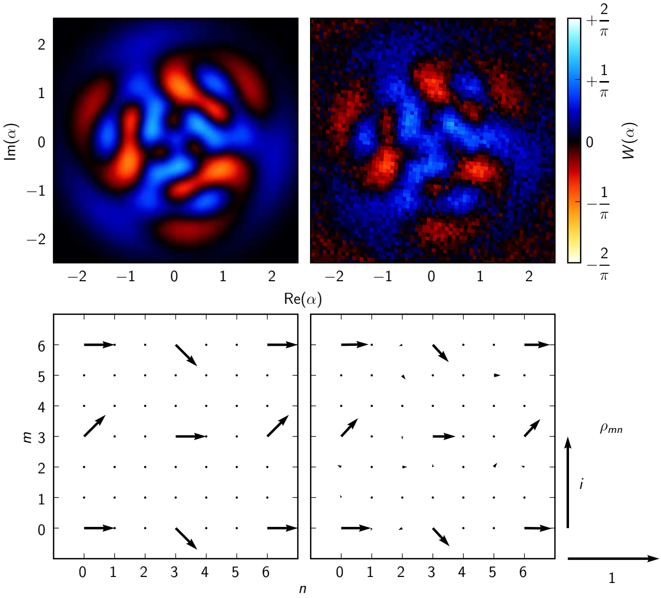


Fidelity:

$$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.91$$

Controlling phase

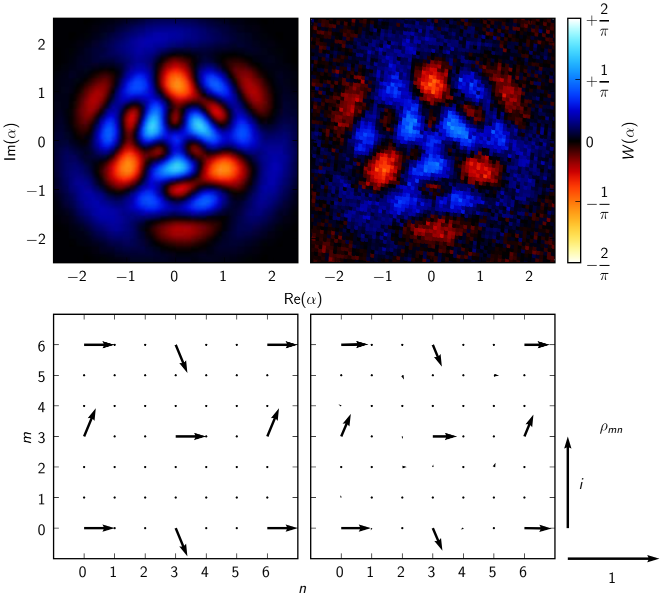
$$|\psi\rangle = |0\rangle + e^{\frac{2}{8}i\pi}|3\rangle + |6\rangle$$



Fidelity:
$$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.91$$

Controlling phase

$$|\psi\rangle = |0\rangle + e^{\frac{3}{8}i\pi}|3\rangle + |6\rangle$$

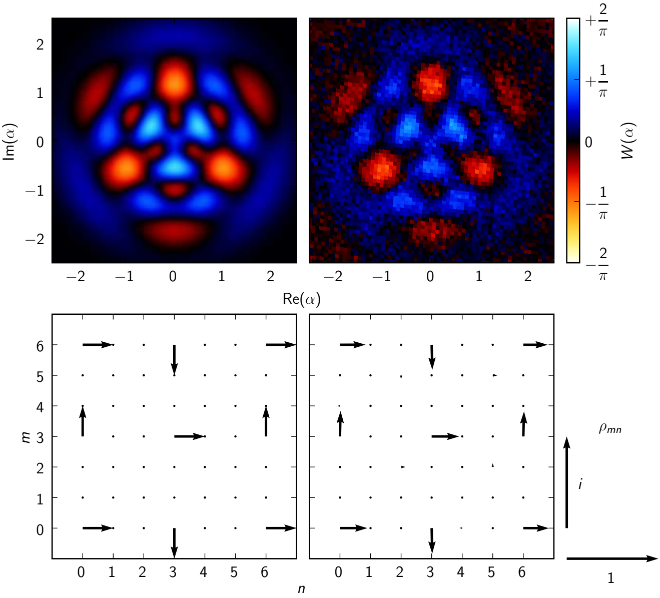


Fidelity:

$$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.92$$

Controlling phase

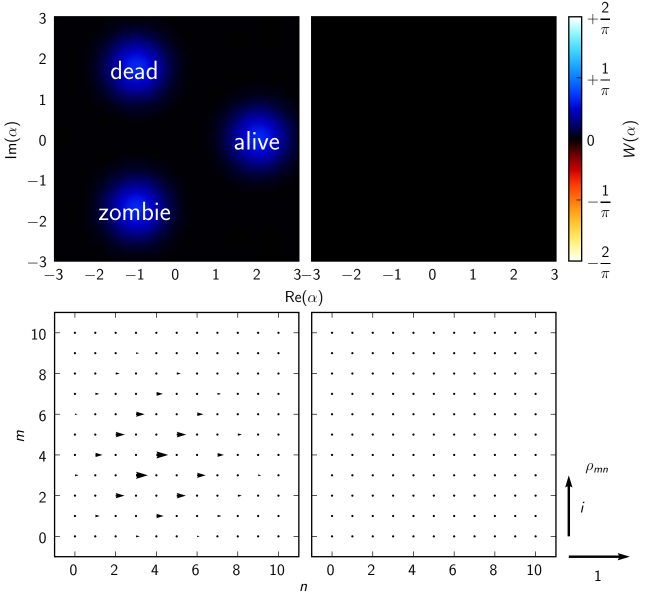
$$|\psi\rangle = |0\rangle + e^{\frac{4}{8}i\pi}|3\rangle + |6\rangle$$



Fidelity:
$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.92$

Voodoo cat

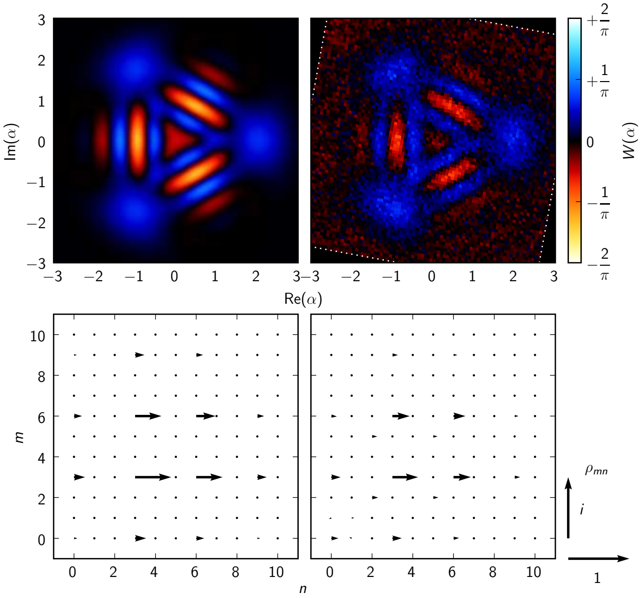
$$|\psi_k\rangle = |2e^{i\frac{2\pi}{3}k}\rangle$$



Voodoo cat

$$|\psi\rangle = \sum_{k=0,1,2} |2e^{i\frac{2\pi}{3}k}\rangle$$

$$\propto \sum_{n=0,3,6,9\ldots} \frac{2^n}{\sqrt{n!}}|n\rangle$$

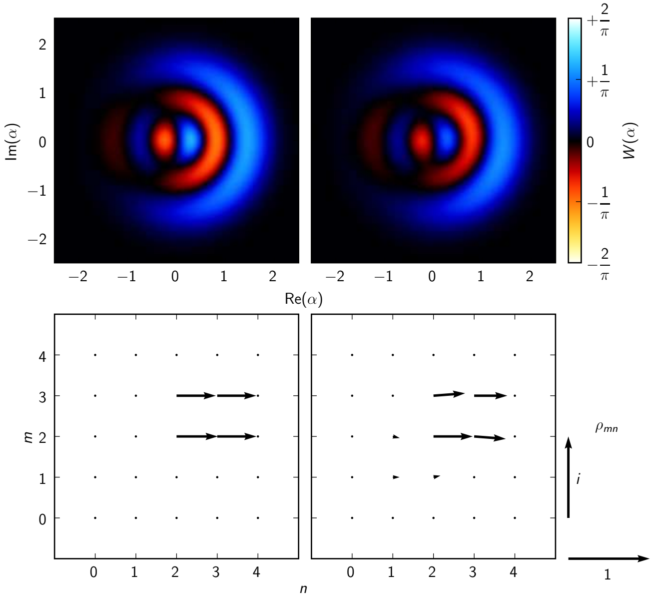


Fidelity:

$F = \sqrt{\langle\psi|\rho|\psi\rangle} = 0.83$

Decay of resonator states (Haohua Wang)

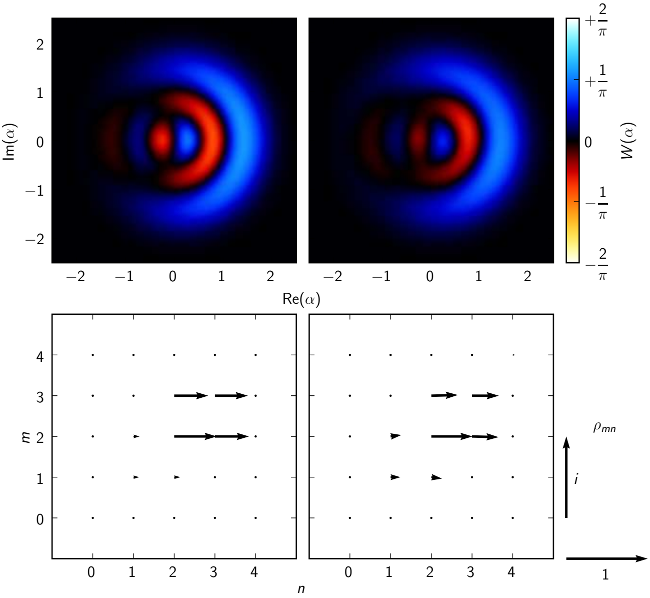
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.05\,\mu$s

Decay of resonator states (Haohua Wang)

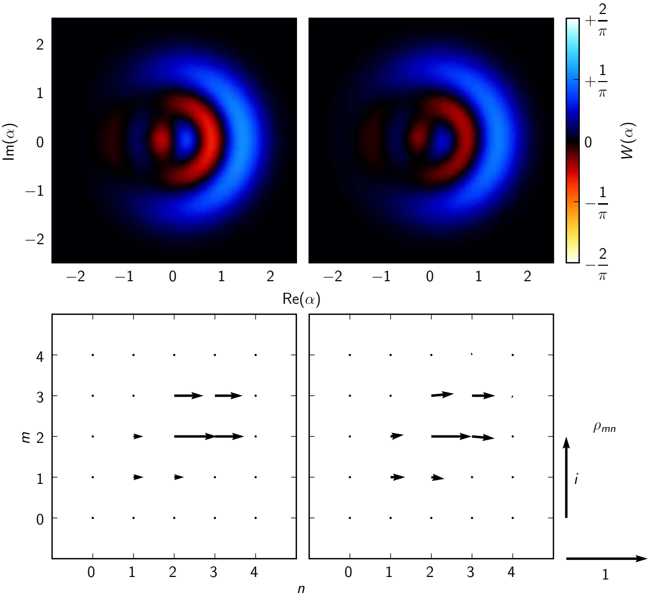
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.20\,\mu s$

Decay of resonator states (Haohua Wang)

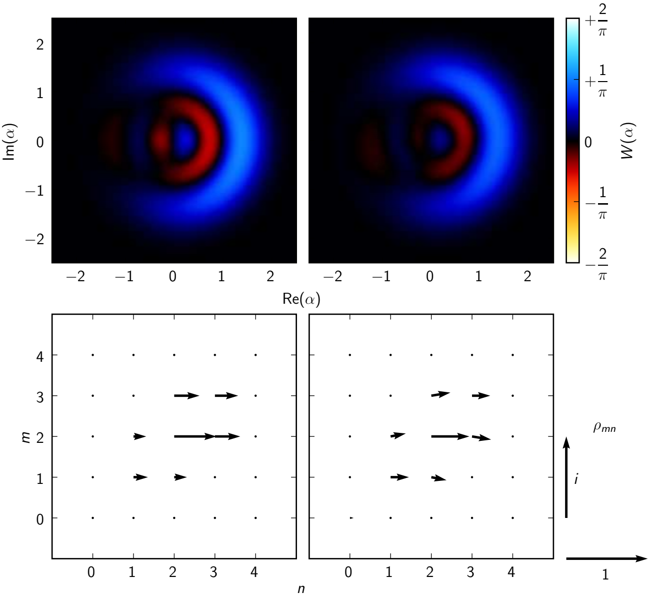
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.35\,\mu s$

Decay of resonator states (Haohua Wang)

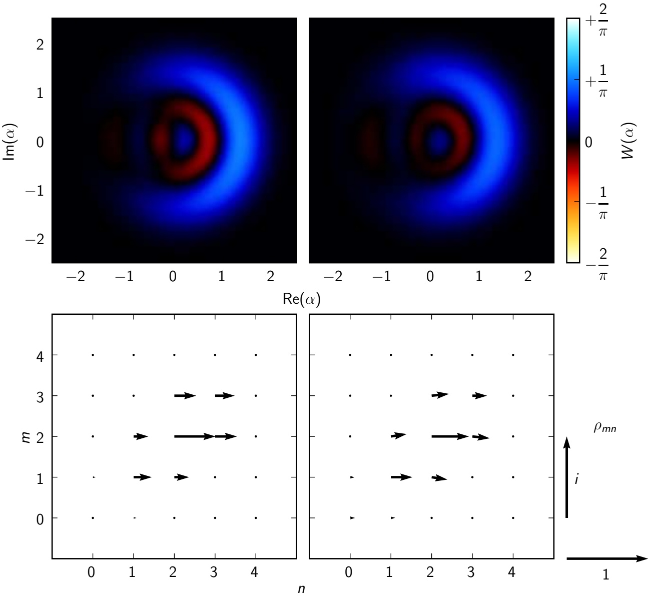
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.50\,\mu$s

Decay of resonator states (Haohua Wang)

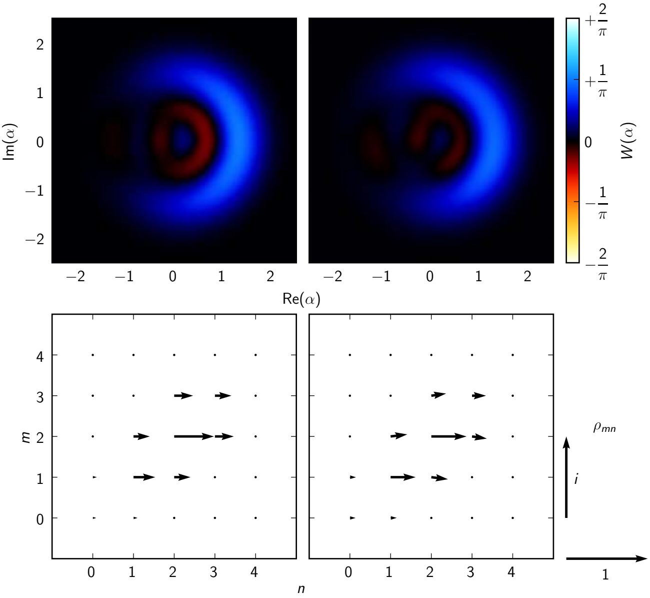
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.65\,\mu$s

Decay of resonator states (Haohua Wang)

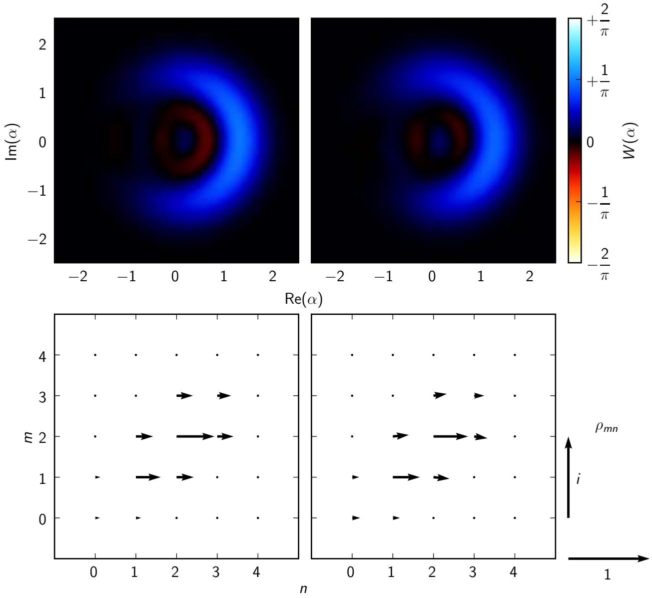
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.80\,\mu$s

Decay of resonator states (Haohua Wang)

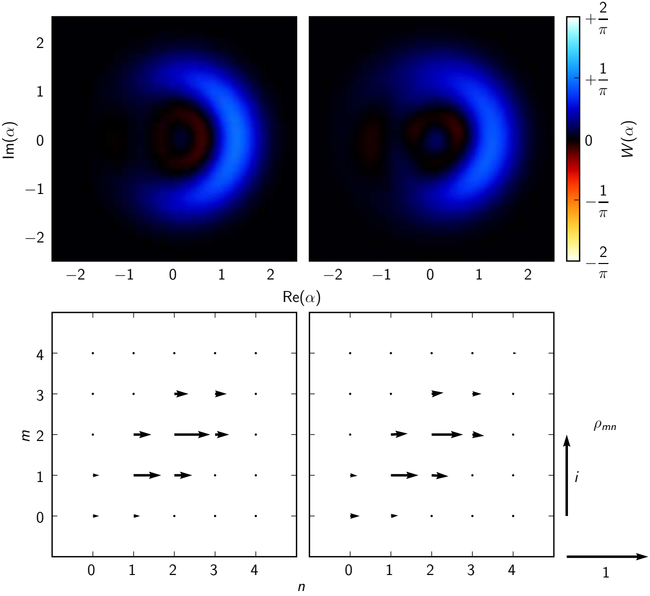
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 0.95\,\mu$s

Decay of resonator states (Haohua Wang)

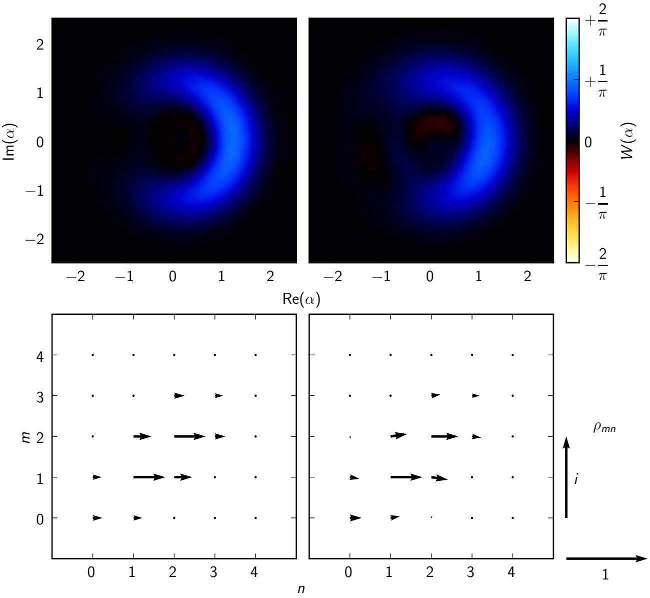
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 1.1\,\mu$s

Decay of resonator states (Haohua Wang)

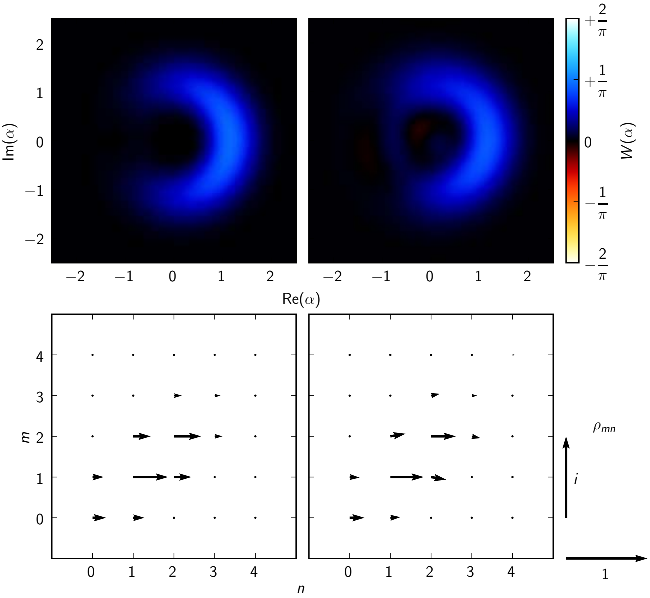
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 1.4\,\mu$s

Decay of resonator states (Haohua Wang)

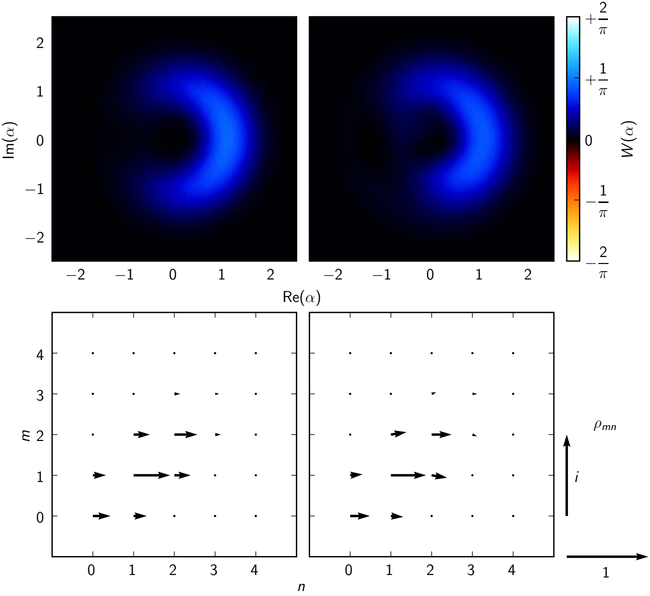
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 1.7\,\mu s$

Decay of resonator states (Haohua Wang)

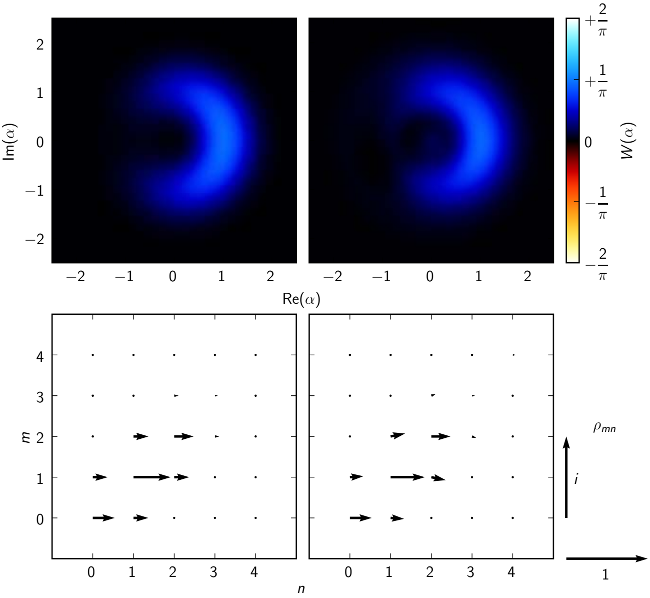
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 2.0\,\mu$s

Decay of resonator states (Haohua Wang)

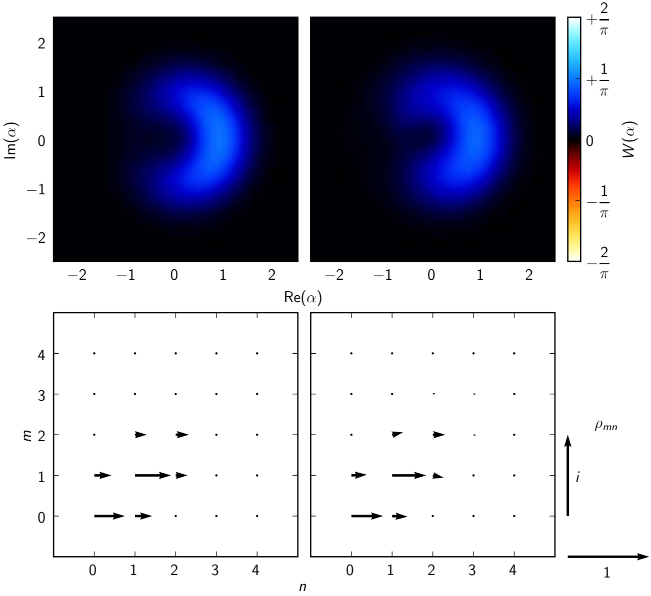
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 2.3\,\mu s$

Decay of resonator states (Haohua Wang)

$|\psi\rangle = |2\rangle + |3\rangle$

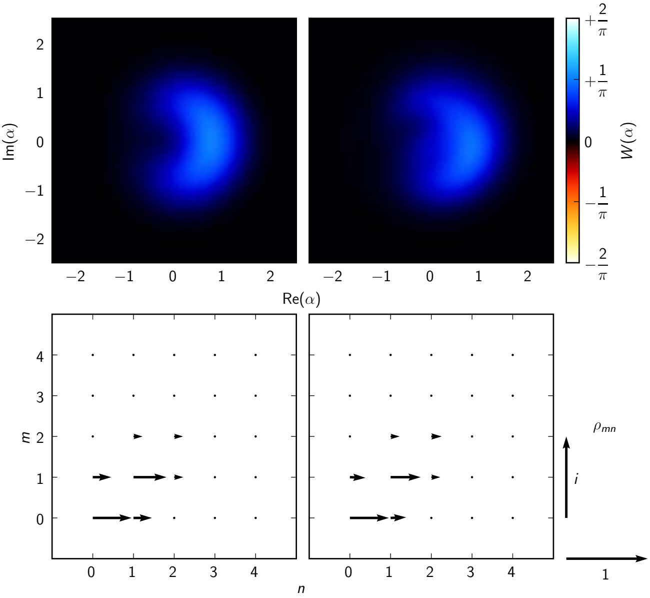


Delay:

$\tau = 2.9\,\mu$s

Decay of resonator states (Haohua Wang)

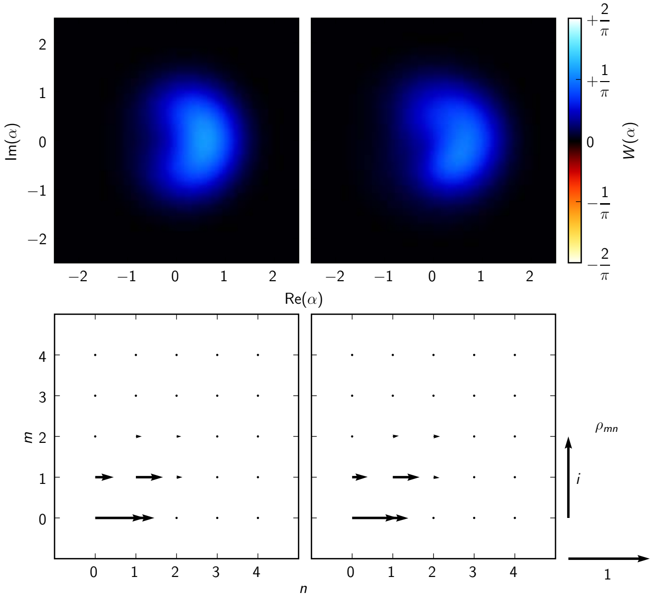
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 3.5\,\mu$s

Decay of resonator states (Haohua Wang)

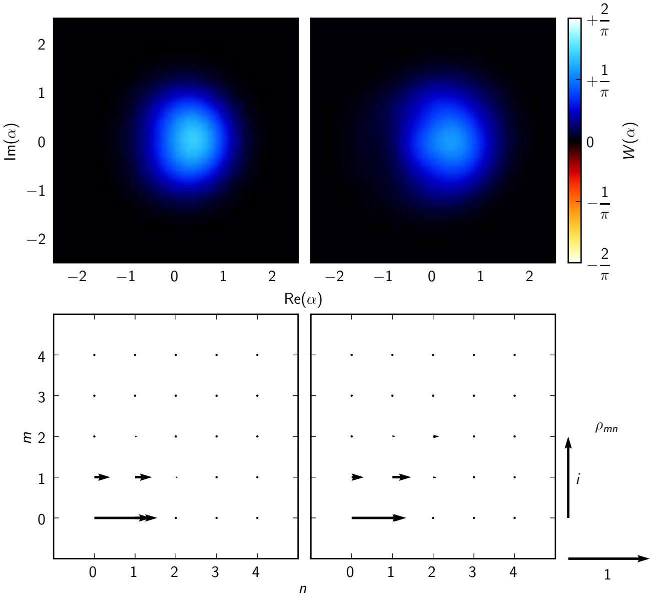
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 4.4\,\mu$s

Decay of resonator states (Haohua Wang)

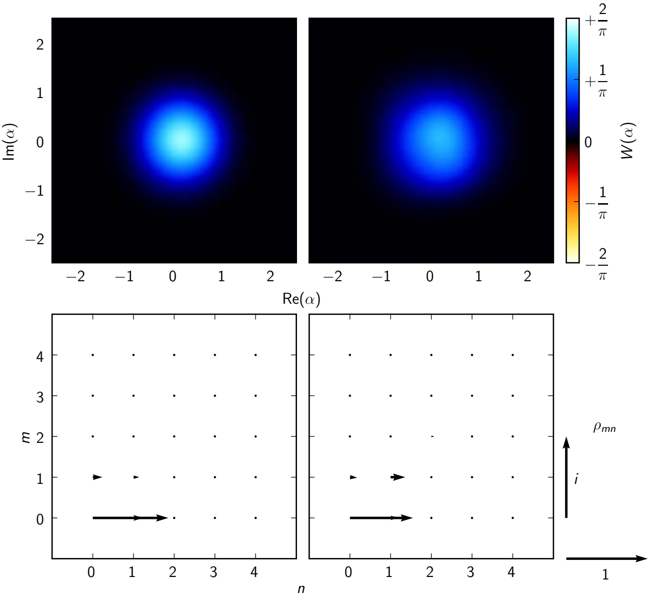
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 6.0\,\mu$s

Decay of resonator states (Haohua Wang)

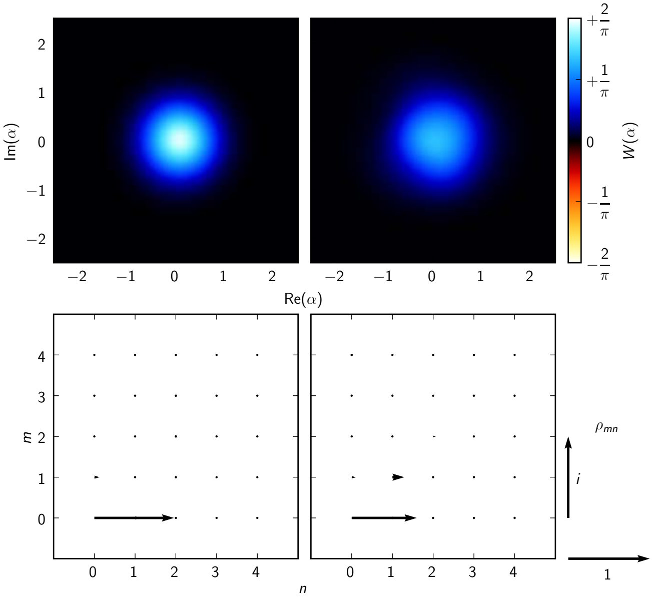
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 9.0\,\mu$s

Decay of resonator states (Haohua Wang)

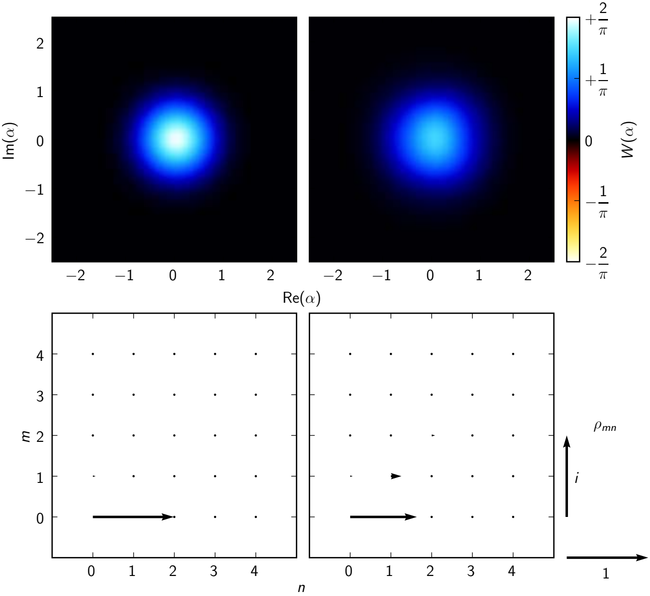
$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 12\,\mu s$

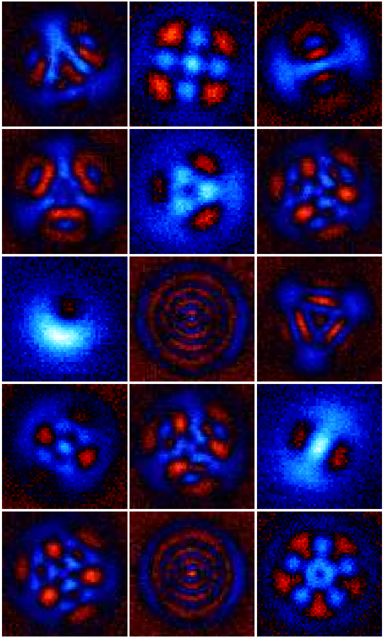
Decay of resonator states (Haohua Wang)

$|\psi\rangle = |2\rangle + |3\rangle$



Delay:
$\tau = 15\,\mu$s

Conclusions



Full control over qubit state extended to resonator:

- arbitrary states
  ($N < 10$ due to coherence)
- deterministic generation
- full characterization

Max Hofheinz, H. Wang, M. Ansmann, R. Bialczak, E. Lucero, M. Neeley, A. O'Connell, D. Sank, M. Weides, J. Wenner, J.M. Martinis, A.N. Cleland

Fock states: Nature **454**, 310–314 (2008)
~ decoherence: H. Wang, PRL **101**, 240401 (2008)
Arbitrary states: Nature **459**, 546–549 (2009)
~ decoherence: H. Wang, PRL **103**, 200404 (2009)

Funding: IARPA, ARO, NSF

Superconducting circuits: Microwave quantum optics

atom	$\longleftrightarrow$	Josephson qubit
optical cavity	$\longleftrightarrow$	LC or wave-guide resonator
light	$\longleftrightarrow$	microwaves ($\nu \sim 7\,\mathrm{GHz}$)

Advantages:

- Qubits and cavities can be coupled at will
- Microwave signal waveforms can be fully controlled

Drawbacks:

- Low photon energy requires low temperatures $T < 50\,\mathrm{mK}$
- Large solid state system limits coherence times

Calibrations

- impulse response (sampling scope)
- imperfections of IQ-mixer (spectrum analyzer)
- cable response (qubit as sampling scope)

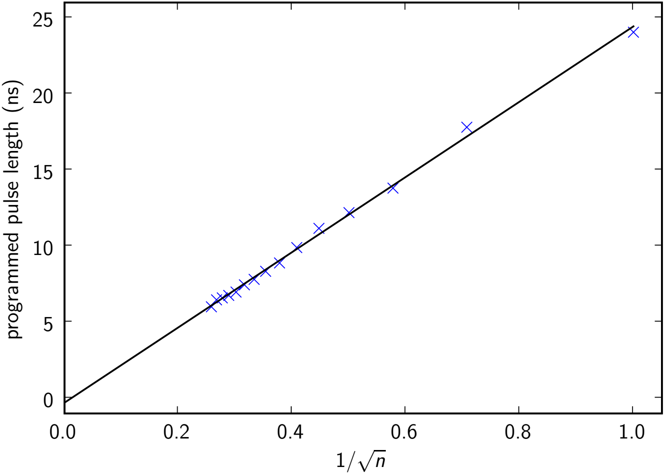
- various parameters for readout SQUID
- π pulses (amplitude and frequency)
- measure pulse amplitude
- swap pulse amplitude
- swap pulse time for each photon number
- first order correction for finite rise time of swap pulses
- qubit/resonator dephasing rate when off resonance
- resonator displacement/drive amplitude ratio
- resonator drive phase
- readout visibility

BUT:

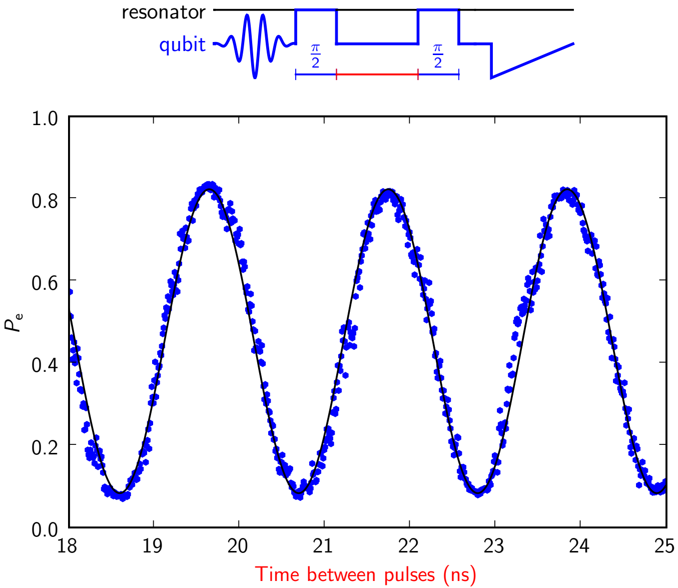
- no per-state calibrations; just run the calculated sequence

Calibrating the swap pulse length

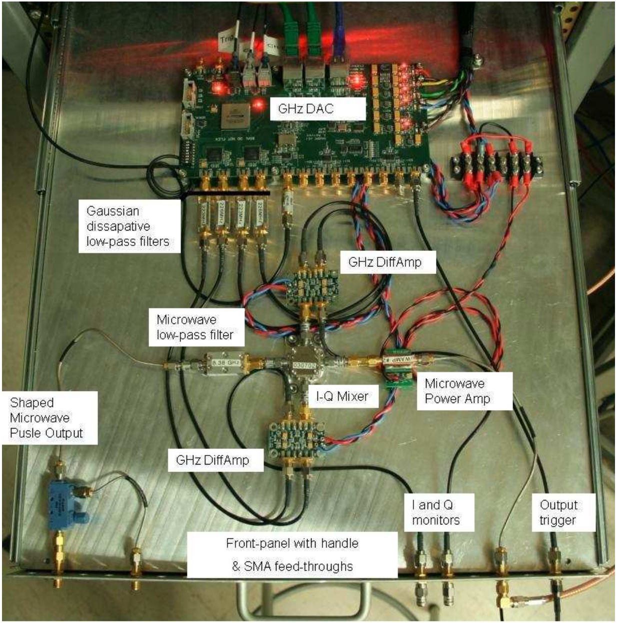
Calibrate with the pulse lengths from the Fock state tune-up.



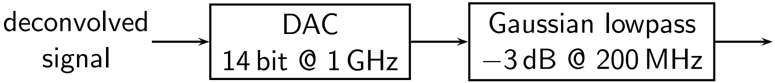
Detuning time calibration: Qubit–resonator Ramsey fringes

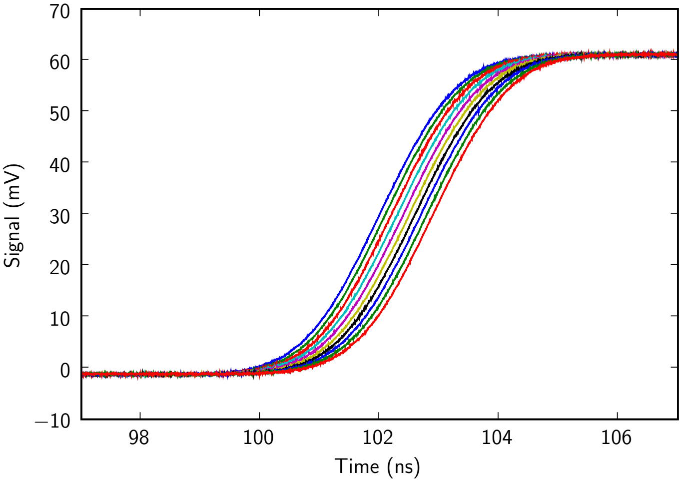


Custom microwave electronics



Sub-ns timing resolution with a 1 GHz DAC





Sub-ns timing resolution with a 1 GHz DAC